ECN

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THE NETHERLANDS

Subject Supply of Meteorological and Oceanographic data for Borssele Wind Farm Zone Period 26 January 2017 – 27 February 2017 (Lot1)

Dear Sir/Madam,

The following two Meteorological and Oceanographic data reports produced by Fugro OCEANOR AS for Lot1 measurement campaign have been reviewed by ECN Wind Energy:

1. Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ)
   Monthly Progress Report : 26 January – 27 February 2017.
   Reference No: C75339_MPR16_R1
2. Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ)
   Validation report : 26 January – 27 February 2017.
   Reference No: C75339_VAL16_R1

ECN has found that the above referenced reports provide a sufficient detail for potential users of the provided data to perform analysis.

Please note that the provided dataset (Period 16 , Version 1 dd. 20170301) can be retrieved via the website : http://offshorewind.rvo.nl/studiesborssele. It should also be noted that in the documents it is mentioned that additional Water Level Sensor data will become available after retrieving the sensor. This data is at the present moment not available via the website and is also not part of this review. Additional actions need to be taken after the data becomes available.

Yours sincerely,

Hans Verhoef
Project Leader Measurements

TESTING RvA L 324 · ilac-MRA	ECN is ISO / IEC 17025 accredited for meteorological measurements.

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THE NETHERLANDS ENTERPRISE AGENCY (RVO)

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ)
Monthly Progress Report: 26 January - 27 February 2017

Reference No: C75339_MPR16_R1
22 March 2017

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Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ): C75339_MPR16_R1				
Rev	Date	Originator	Checked & Approved	Issue Purpose
0	03.03.2017	Ola Storås	Arve Berg	Draft report.
1	21.03.2017	Ola Storås	Arve Berg	Final report

Rev 1 – 21 March 2017	Originator	Checked & Approved
Signed:		

This report is not to be used for contractual or engineering purposes unless the above is signed where indicated by both the originator of the report and the checker/approver and the report is designated 'FINAL'.

TABLE OF CONTENT

SUMMARY

The Seawatch Wind Lidar buoy is deployed at the Borssele Wind Farm Zone (BWFZ). This monthly report summarizes the activities during the period 26 January - 27 February 2017, and presents time series plots of the data collected during this period.

The buoy was first deployed on 11th June 2015 at 15:55 UTC, and a bottom mounted tide gauge (WLR) was deployed at 16:15 UTC on the same day. In total 3 different buoys has been used for the measurements. In the whole 2015 and until 19th January 2016 the Seawatch Wind Lidar buoy WS149 was used for the measurements. On the 12th February 2016 the SW Wind Lidar buoy WS157 was deployed at the same position. This buoy was used for the measurements until 20th July 2016 and was then swapped with SW Wind Lidar buoy WS156. This buoy was then used until 12th December 2016 when it was swapped with SW Wind Lidar buoy WS157.

Due to a few minor gaps in the time series it took 31.535 days to collect 30.5 days of good wind profile data for the present period.

1. INTRODUCTION

The Seawatch Wind Lidar buoy with serial no. WS149 was first deployed at the Borssele Wind Farm Zone (BWFZ) in the Dutch sector of the North Sea on 11 June 2015 at 15:55 with the bottom mooring weight at position 51° 42.41388' N, 3° 2.07708' E. The water depth at this location is approximately 30 m. A bottom mounted water level recorder (WLR) was deployed near the buoy at position 51° 42.4362' N, 3° 02.1030' E at the same time, transmitting data to the buoy in real time data via an acoustic link. Unfortunately the acoustic link broke down on 8th July 2015 so water level data are no longer received in real time, but the data are stored in the WLR for download when it is recovered.

A spare WLR with internal data storage only was deployed on 18th December 2015 to ensure water level data recovery.

In total 3 different buoys has been used for the measurements. In the whole 2015 and until 19th January 2016 the Seawatch Wind Lidar buoy WS149 was used for the measurements. The Lidar on Buoy WS149 stopped working on 26 December 2015 due to a technical problem with its Lidar power switch. After a long period of unworkable weather conditions, and some delay due to vessel unavailability, the buoy was recovered for repair on 19 January 2016. The root cause of the problem was found and measures were taken to prevent it from happen again.

On the 12th February 2016 the SW Wind Lidar buoy WS157 was deployed at the same position at 13:00. This buoy was in successful operation in position until recovery for fuel refill on 20th July 2016 and was then swapped with SW Wind Lidar buoy WS156 at 10:00 UTC. Buoy WS156 was then used until 12th December 2016 when it was swapped with SW Wind Lidar buoy WS157.

All the buoys used have been pre-deployment validated at Fugro OCEANOR test site according to the Carbon Trust OWA roadmap, approved by DNV-GL (reports are published on RVO web page for offshore wind).

This reporting period extends from 26 January at 23:00 until 27 February 2017 at 11:50, and contains 30.5 days of wind profile data. The time reference used in this report is UTC.

2. Instrumentation and measurement configuration

The buoy is a Seawatch Wind Lidar Buoy based on the original Seawatch Wavescan buoy design with the following sensors:

- Wavesense: 3-directional wave sensor
- Xsens 3-axes motion sensor
- Gill Windsonic M acoustic wind sensor
- Vaisala PTB330A air pressure sensor
- Vaisala HMP155 air temperature and humidity sensor
- Nortek Aquadopp 600kHz current profiler.
- ZephIR 300S Lidar.

An independent self-recording Aanderaa SeaGuard WLR tide gauge is located on the bottom. The WLR transmits data to the buoy via an acoustic link.

The buoy with mooring as deployed is presented in Figure 2.1, including the mooring for the WLR.

The measurement setup is detailed in Table 2-1. Details of sensor types and serial number can be found in Appendix A.

Table 2-1 Configuration of measurements by the Seawatch Wind Lidar buoy at Borssele Wind Farm Zone (BWFZ).

Instrument type	Sensor height (m)	Parameter measured	Sample height[2] (m)	Sampling interval (s)	Averaging period (s)	Burst interval (s)	Trans-mitted?
Wavesense 3	0	Heave, pitch, roll, heading	0	0.5	Time series duration: 1024 s	600	No
		Sea state parameters (1)	0	600	1024	600	Yes
Xsens		Heave,east,north acceleration, q0,q1,q2,q3 (attitude quaternion)	0	0.5	N/A	3600	No
Gill Windsonic M	4.1	Wind speed, wind direction	4.1	1	600	600	Yes
Vaisala PTB330A	0.5	Air pressure	0.5	30	60	600	Yes
Vaisala HMP155	4.1	Air temperature Air humidity	4.1	5	60	600	Yes
Nortek Aquadopp	-1	Current speed and direction profile, water temperature (at 1 m depth)	-4 -6 … -30 (14 levels)	N/A	600	600	Yes
ZephIR 300S Lidar	2	Wind speed and direction at 10 heights (The 11th level, the so called reference level which is not configurable, is also located at 40 m and referred to as 40.0 Ref.)	30.0 40.0 40.0 ref 60.0 80.0 100.0 120.0 140.0 160.0 180.0 200.0	≈ 17.4 s[1]	600	600	Yes
Aanderaa WLR (SeaGuard) via acoustic link	-30	Water pressure Temperature	-30	600	60	600	Yes[3]

1) This is the approximate time between the beginning of one sweep of the profile and the next one, the interval may vary slightly. The ZephIR sweeps one level at a time beginning at the lowest one, and after the top level has been swept it uses some time for calculations and re-focusing back to the lowest level for a new sweep.

2) Height relative to actual sea surface. The depth of the WLR is an approximate number.

3) The WLR data are not transmitted after 8 July 2015 due to failure of the acoustic link. An additional self-contained WLR was deployed 18 December 2015 to ensure data recovery.

Table 2.2 Definitions of wave parameters presented in this report

H	Individual wave height
Hmax	= Max(H): Height of the highest individual wave in the sample, measured from crest to trough
m0, m1, m2, m4, m-1, m-2	Moments of the spectrum about the origin: $\int f^k S(f)df$ where $S(f)$ is the spectral density and the wave frequency, f, is in the range 0.04 - 0.50 Hz
Hm0	Estimate of significant wave height, Hs, $Hm0 = 4\sqrt{m0}$
Tp	Period of spectral peak = $1/f_p$, The frequency/period with the highest energy
Tm01	Estimate of the average wave period; $Tm01 = m0/m1$
Tm02	Another estimate of the average wave period; $Tm02 = \sqrt{\frac{m0}{m2}}$
ThTp	Mean wave direction at the spectral peak ("The direction of most energetic waves")
Mdir	Wave direction averaged over the whole spectrum
	Directions are given in degrees clockwise from north, giving the direction the waves come from. (0° from north, 90° from east, etc.)

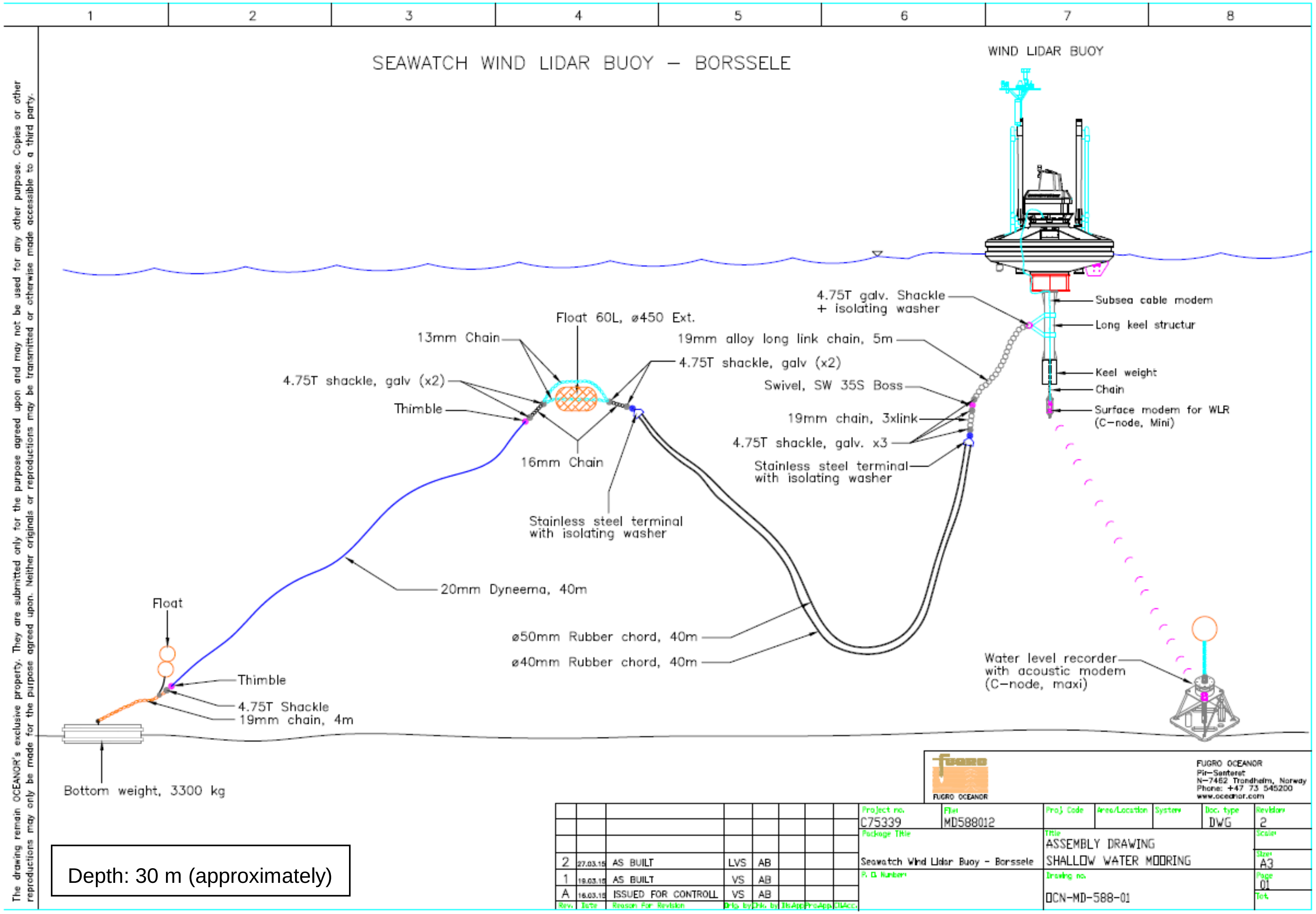

Figure 2.1 Mooring design for the Wind Lidar Buoy and Seaguard WLR bottom unit as deployed at Borssele Wind Farm Zone (BWFZ) 11 June 2015.

3. Summary of activities

3.1 Buoy operation

The Seawatch Wind Lidar buoy with serial no. WS149 and a bottom mounted Water Level Recorder (SeaGuard WLR) were deployed at the Borssele Wind Farm Zone in the Dutch sector of the North Sea on 11 June 2015. The buoy was deployed at 15:55 with the bottom mooring weight at position 51° 42.41388' N, 3° 2.07708' E. A bottom mounted WLR was deployed at position 51° 42.4362' N, 3° 02.1030' E. The WLR transmitted data to the buoy in real time data via an acoustic link[1]. The sounder depth was recorded as approximately 30 m.

The Lidar on buoy WS149 stopped working on 26 December 2015, and after a long period of mainly unworkable weather conditions, and some delay due to vessel unavailability, the buoy was recovered for repair on 19 January 2016. The root cause of the problem was found and measures were taken to prevent it from happen again.

The buoy was replaced by the spare buoy WS157 which was deployed at exactly the same position on 12 February 2016. These operations were carried out using the Multrasalvor 3.

The spare buoy WS157 was swapped with WS156 on 20 July 2016. The WS156 was previously used at the Borssele Wind Farm Zone (BWFZ) in position labelled "lot 2" and recovered for service and fuel refill 7 July 2016. Buoy WS156 was then used until 12th December 2016 when it was swapped with SW Wind Lidar buoy WS157. Deployment sheet for WS157 is given in Appendix A.

An attempt to recover the WLR module was made on the July survey, but no signal/ping was received from the module. The WLR was therefore not recovered

3.2 Health, Safety and Environment

No sea operation has been performed in the present reporting period.

[1] The acoustic link failed and the transmissions of water pressure data from the WLR stopped on 8th July 2015. It is expected that the internal recording of data in the WLR will continue undisturbed until it is recovered.

4. Results

4.1 Summary of results and data return

The buoy transmitted data continuously from all sensors from 26 January at 23:00 until 27 February 2017 at 11:50, with the exception of some minor gaps. The longest data gaps occurred on 6th of February. For the short gaps in the Lidar data the received data are replaced by the "missing data" flag at all heights. Due to the gaps it took 31.535 days to collect 30.5 days of good wind profile data[2].

The air temperature and humidity sensor has previously been reported to have low availability due to repeated subsequent equal values. There is no gap in the data, but two or more subsequent equal values have been interpreted as a sensor error and the value has been replaced by NaN. The Vaisala HMP155 sensor is reporting two values; air temperature and relative humidity. The filtering we have applied earlier had the condition that if **both** air temperature and humidity reported repeated values, the repeated value was replaced by NaN. The data resolution for air temperature has been close to 0.1 ^{o}C and the data resolution for humidity has been 0.1 % in the buoy config. In other words we have applied an acceptance criteria saying that air temperature must change more than 0.1 ^{o}C **or** the humidity must change more than 0.1 % **in 10 min** in order for the data to be accepted as good. This is obviously **too strict** and we have unfortunately removed good values from the data set in previous periods causing a too low availability for air temperature and humidity.

We have now modified the acceptance criteria to the condition that if **both** air temperature and humidity reported repeated values for **more than 3 subsequent measurements** (30 min), the repeated value is replaced by NaN.

The number of hours of good data compared to the total obtainable hours of data is presented in Table 4-1.

Table 4-1 Data return during the period 26 January at 23:00 - 27 February 2017 at 11:50

Measurement device	Length of data period (days)	Length of data set (days)	Average availability (%)
Lidar wind profile sensor	31.535	30.500	96.718
Wave sensor	31.535	31.235	99.053
Current velocity and direction sensor	31.535	31.299	99.251
Atmospheric pressure sensor	31.535	31.305	99.273
Air temperature sensor	31.535	30.687	97.314
Water Level Sensor *	31.535	0	0.00

* The real time transmitted water level data are unexpectedly lost due to breakdown of the acoustic link. However, the complete data series will be recovered when the instrument is recovered.

[2] Additional gaps in the real time transmitted Turbulence Intensity (TI) data are caused by breaks in the satellite dial-up transmission link. The data that were not received in real time are stored internally in the buoy and will be downloaded from the buoy when it is recovered.

Statistical summary of the collected date is given in table 4.2 - 4.4.

Table 4.2 Average and maximum measured values of wind speeds: 10 min mean and gust from the Gill sensor at 4 m height, 10 min mean speeds at 10 levels from the Lidar. (Heights referred to the sea surface.)

Instrument	Parameter	Height m	Average m/s	Maximum m/s
Gill Windsonic	10 min mean wind speed	4	6.86	18.10
	3-second gust	4	8.70	26.02
ZephIR Lidar	10 min mean wind speed	30	8.86	24.73
		40	9.30	25.55
		60	9.87	26.89
		80	10.28	27.48
		100	10.60	27.10
		120	10.86	28.87
		140	11.08	29.77
		160	11.26	30.94
		180	11.42	31.41
		200	11.52	31.58

Table 4.3 Minimum, average and maximum measured values of meteorological data, wave data and sea surface temperature (at 1 m depth).

Parameter	Unit	Height	Minimum	Average	Maximum
Air Pressure	hPa	1	987.1	1015.4	1030.8
Air Temperature	°C	4	- 0.68	5.38	9.60
Humidity	% R.H.	4	61.4	91.4	103.0
hm0	m	0	0.21	1.06	5.70
hmax	m	0		1.51	12.6
thmax	s	0		5.57	
tm01	s	0		4.26	7.62
tm02	s	0		4.04	7.22
tp	s	0		5.23	10.64
Water Temperature	°C	-1		5.73	6.83

Table 4.4 Average and maximum measured values of current speed from 4 m to 30 m depth.

Depth m	Average cm/s	Maximum cm/s
4	50.4	96.1
6	51.8	98.4
8	51.1	102.0
10	51.7	99.6
12	51.9	96.1
14	50.9	97.3
16	50.5	92.6
18	49.8	93.7
20	49.0	89.1
22	47.9	89.1
24	46.7	87.9
26	45.3	84.4
28	42.1	83.2
30	31.3	80.9

4.2 Presentation of the received data

The following presentations show good data transmitted from the buoy via Iridium satellite during the period 26 January at 23:00 - 27 February 2017 at 11:50.

4.2.1 Meteorological data

The following plots present the air pressure, air temperature, and sea surface temperature. In this period we experienced air temperature below zero on 10th, of February, when the air temperature was down to - 0.7 ^{o}C.

The water temperature sensor is part of the current profiler, the AquaDopp, and data recovery for water temperature is the same as for current profile data.

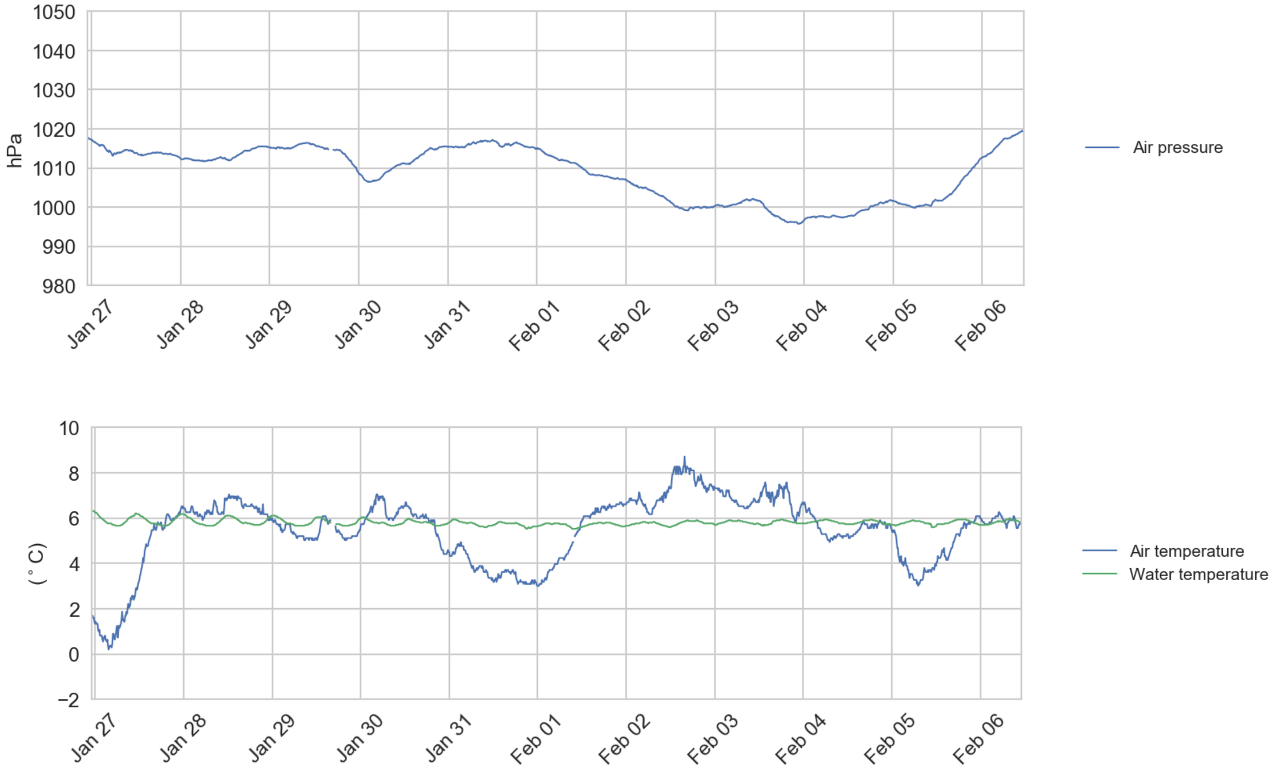

Figure 4.1 Time series plots of air pressure (upper panel), air and water temperature (lower panel), 26 Jan - 6 Feb 2017.

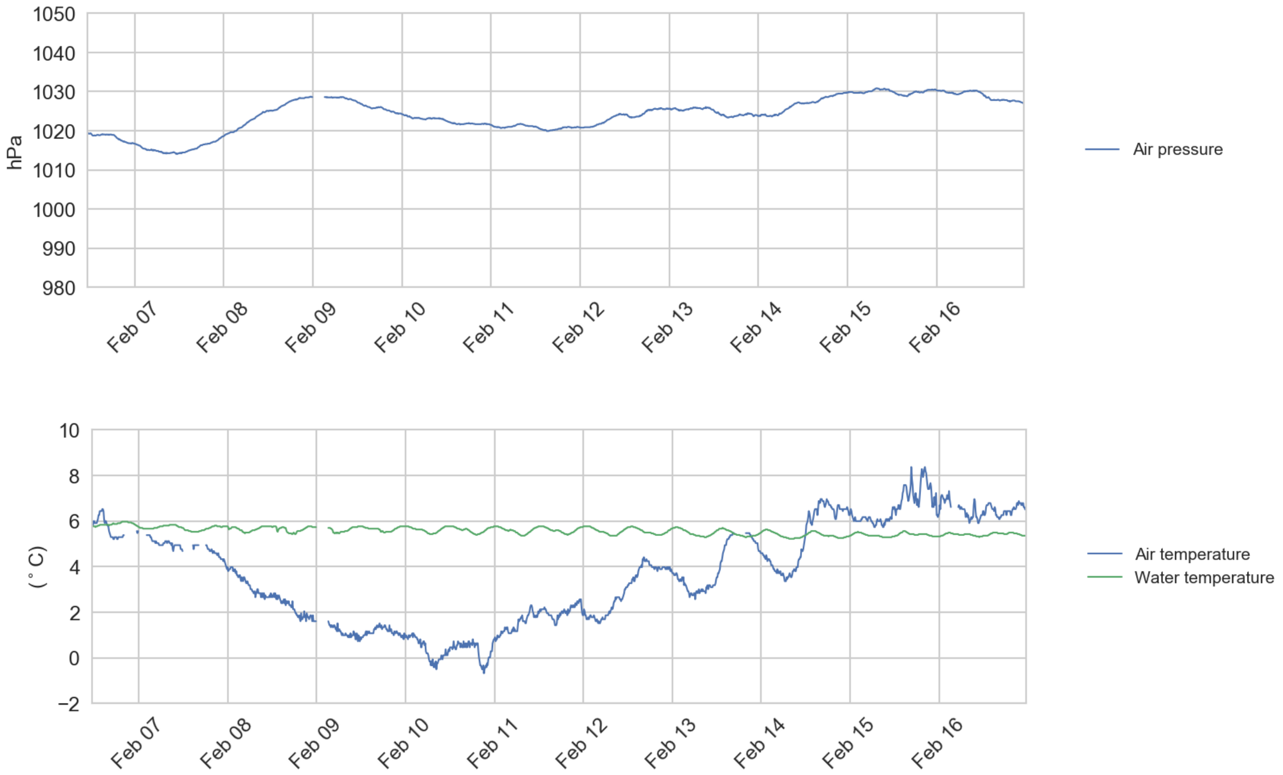

Figure 4.2 Time series plots of air pressure (upper panel), air and water temperature (lower panel), 6 - 16 Feb 2017.

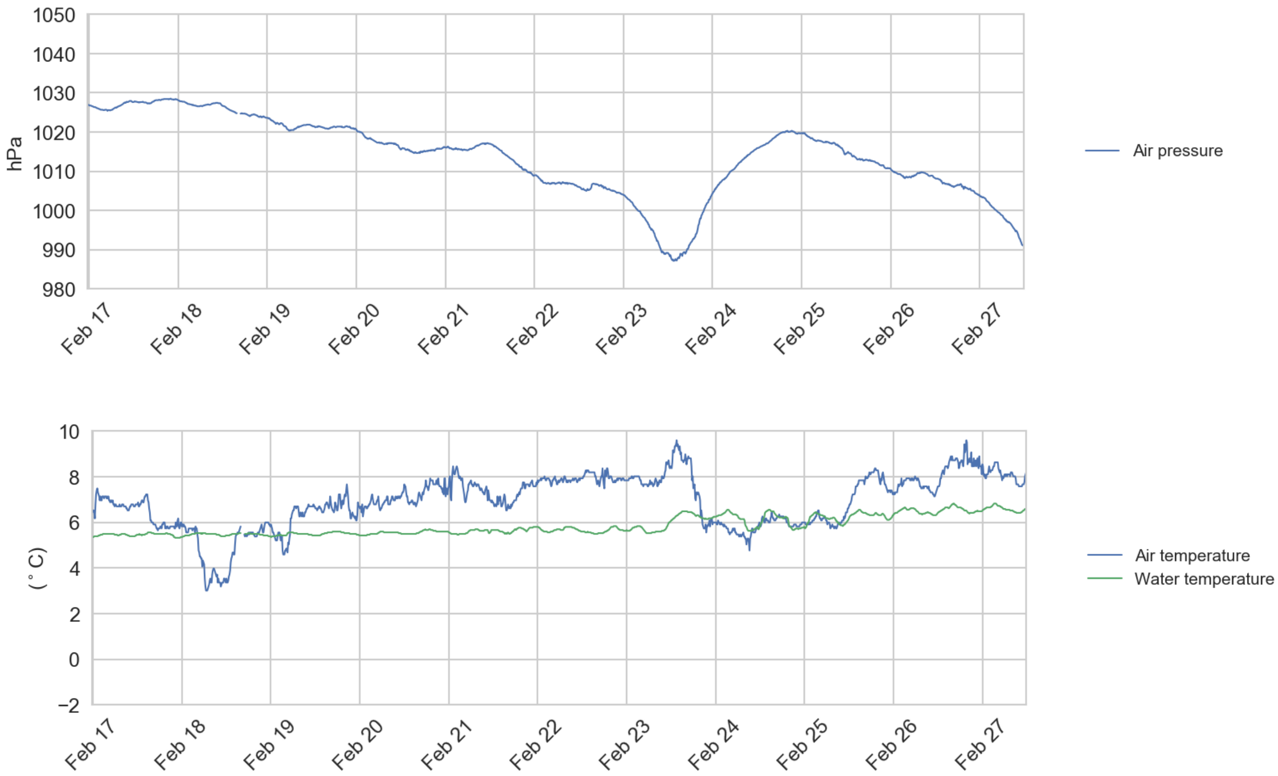

Figure 4.3 Time series plots of air pressure (upper panel), air and water temperature (lower panel), 16 - 27 Feb 2017.

4.2.2 Wave data

The next plots present wave height, period and direction. The wave sensor has generally functioned well. There are only minor data gaps on 29th of January and 9th and 18th of February 2017.

The highest significant wave height (Hm0) measured in this period was 5.7 m from a south-westerly direction (~240°) at 23th of February. Wind speeds of around 25 m/s from west (~270°) were observed in the profile prior to the highest sea states. The highest single wave with a height of 12.6 m was also observed on 23th of February.

The variations in wave height agree well with the wind speeds in general. The average wave period parameters Tm01 and Tm02 show semidiurnal variations which can be explained by the shift in frequency when the waves are travelling along with or opposing the current direction, since the tidal current direction varies in a semi-diurnal pattern.

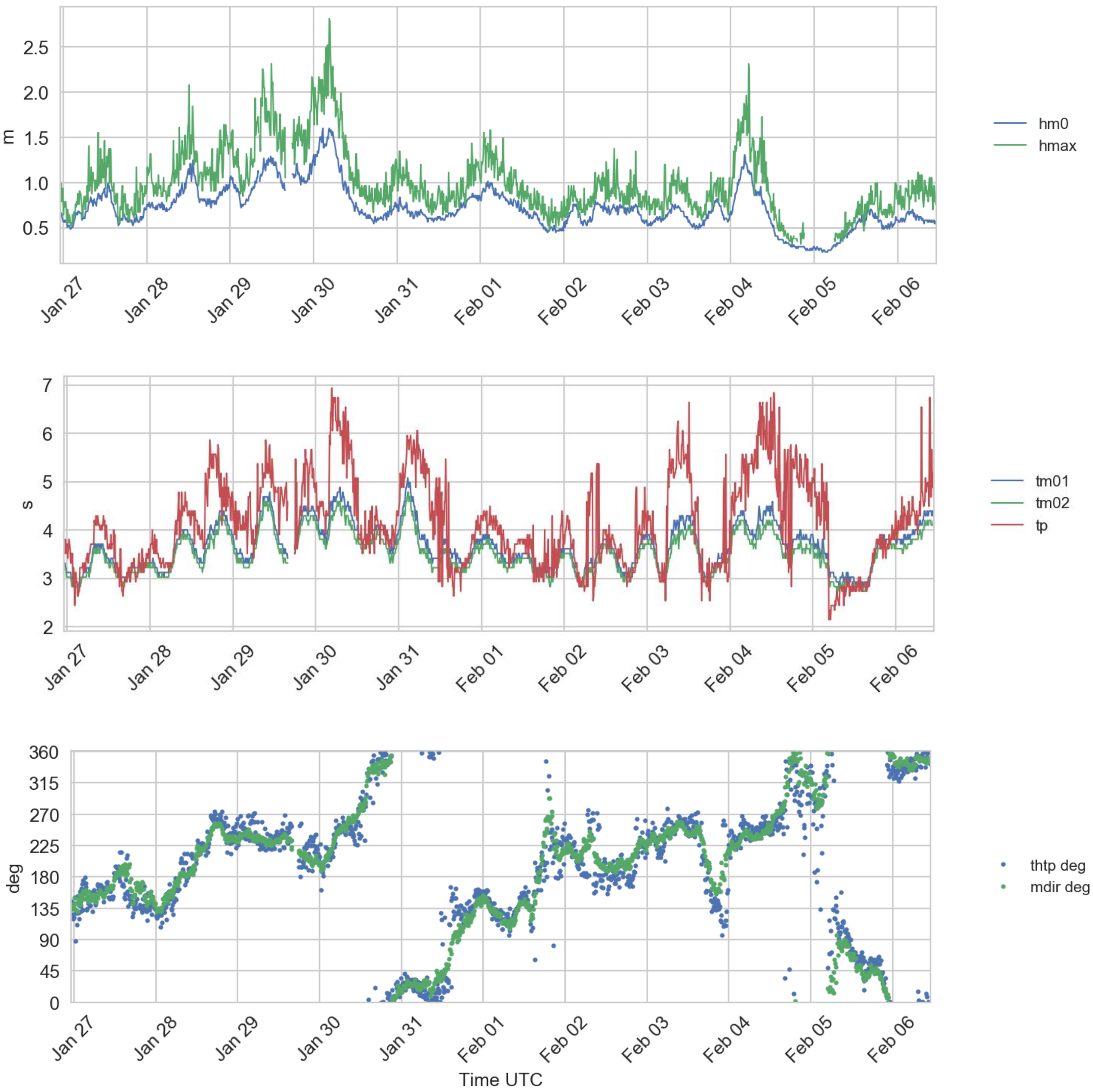

Figure 4.4 Time series plots of wave height (Hm0 and Hmax) (upper panel), wave period (Tm01, Tm02 and Tp) (second panel), and wave direction (ThTp and Mdir) (lower panel), 26 Jan - 6 Feb 2017.

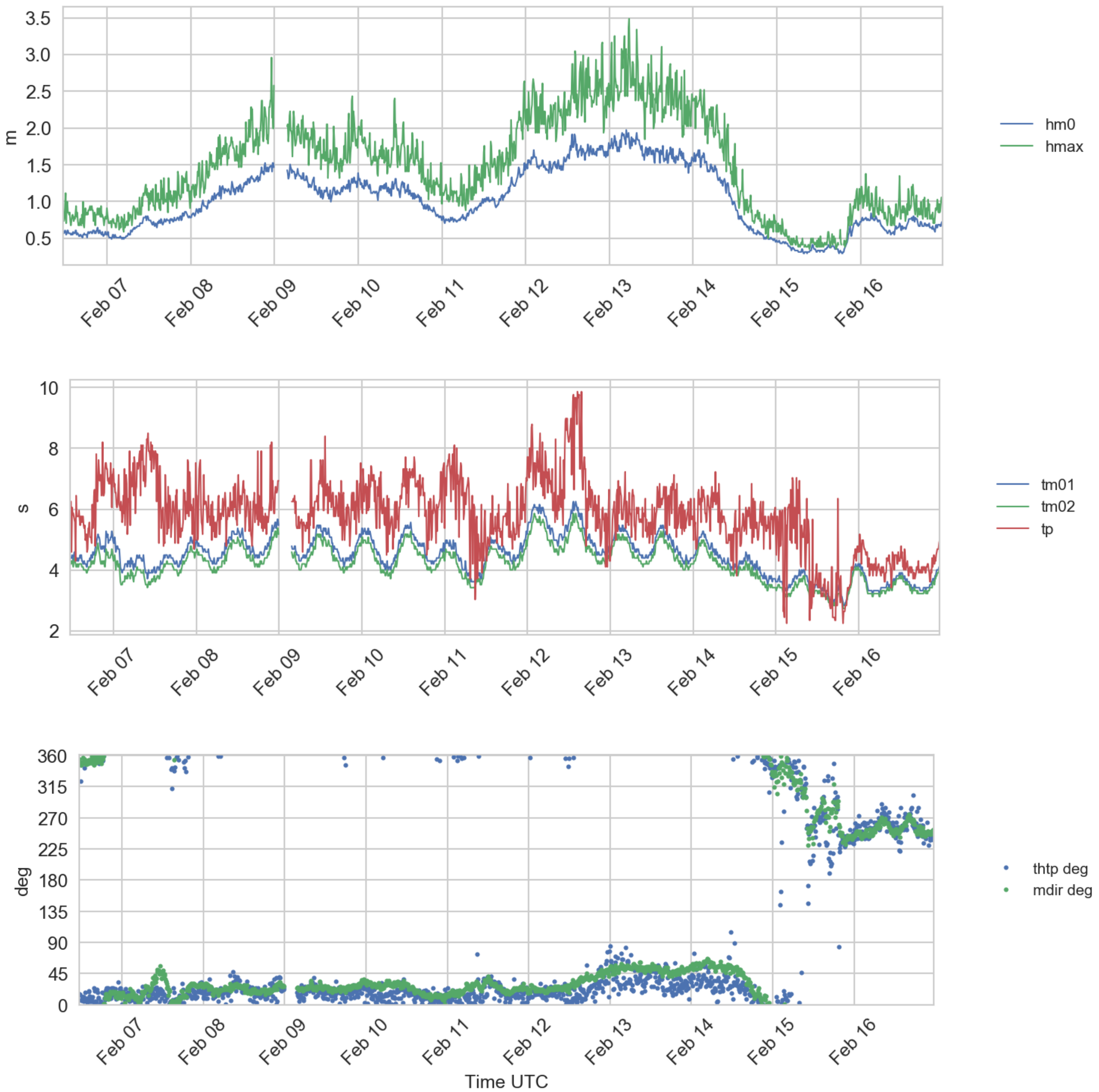

Figure 4.5 Time series plots of wave height (Hm0 and Hmax) (upper panel), wave period (Tm01, Tm02 and Tp) (second panel), and wave direction (ThTp and Mdir) (lower panel), 6 - 16 Feb 2017.

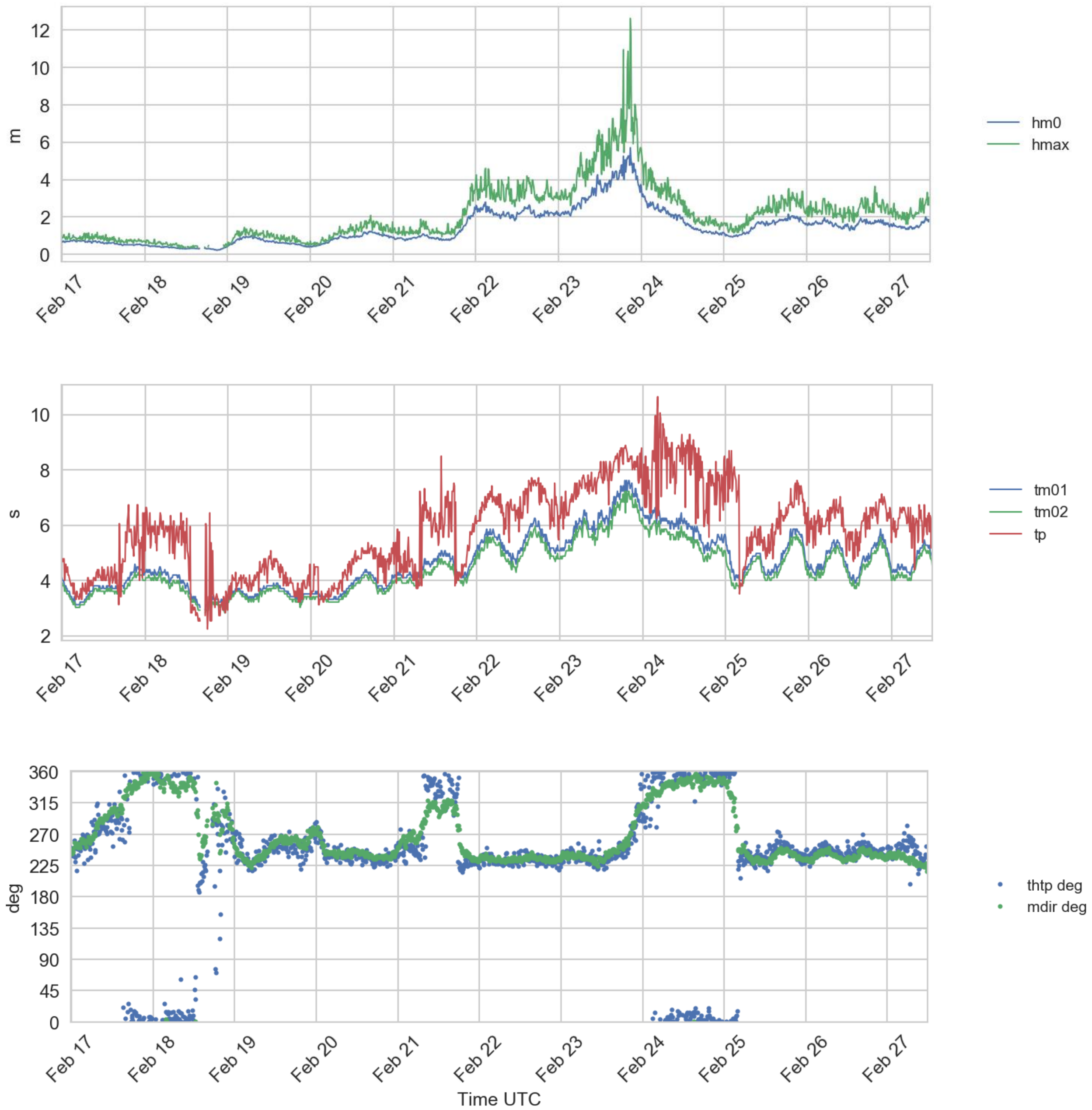

Figure 4.6 Time series plots of wave height (Hm0 and Hmax) (upper panel), wave period (Tm01, Tm02 and Tp) (second panel), and wave direction (ThTp and Mdir) (lower panel), 16 - 27 Feb 2017.

4.2.3 Wind profile data

In the wind and wave direction plots 0° and 360° indicate direction from the north.

The following plots show the wind speed and direction data from the Gill wind sensor mounted at 4 m height on the buoy mast. The data from the Gill sensor are generally good. In this period 10 min mean wind speeds up to 18.1 m/s were measured 23rd February 2017 and gusts up to 26.0 m/s were measured at 4 m above the sea surface also on 23rd February 2017.

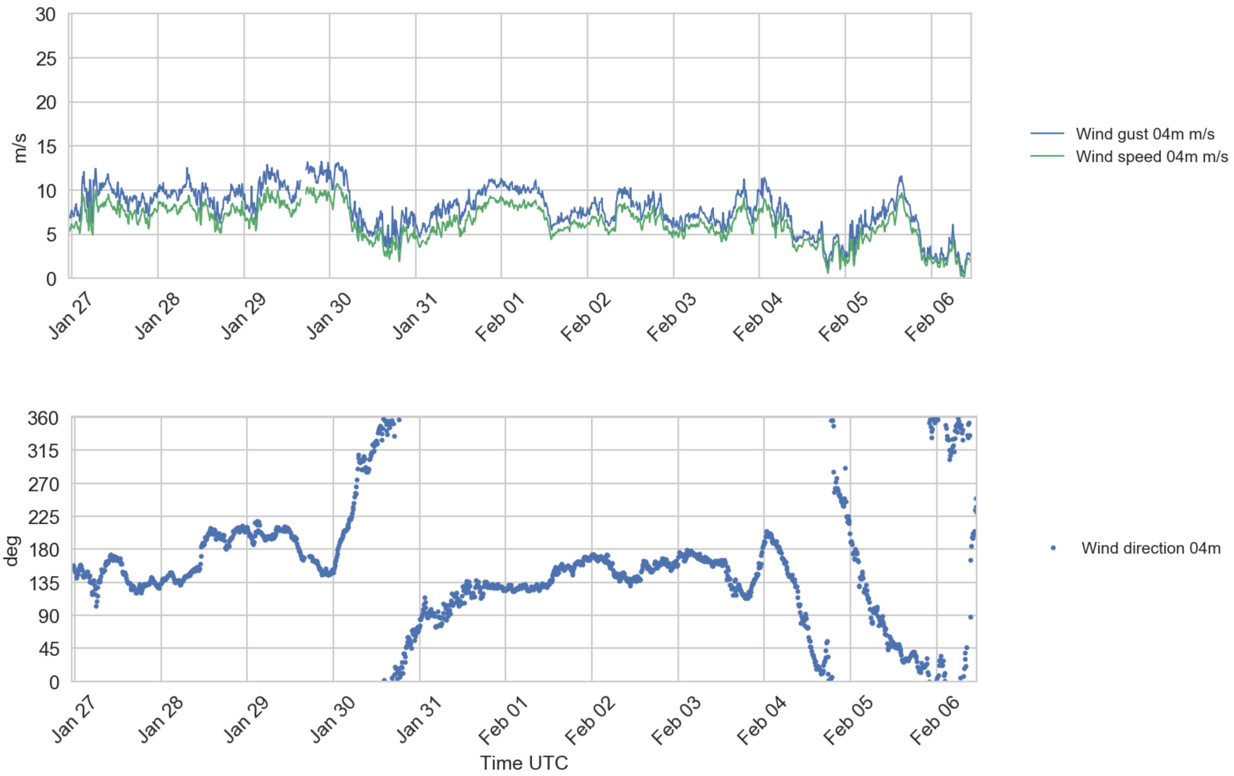

Figure 4.7 Plots of wind speed and gust (upper), and wind direction (lower) at 4 m a.s.l., 26 Jan - 1 Feb 2017.

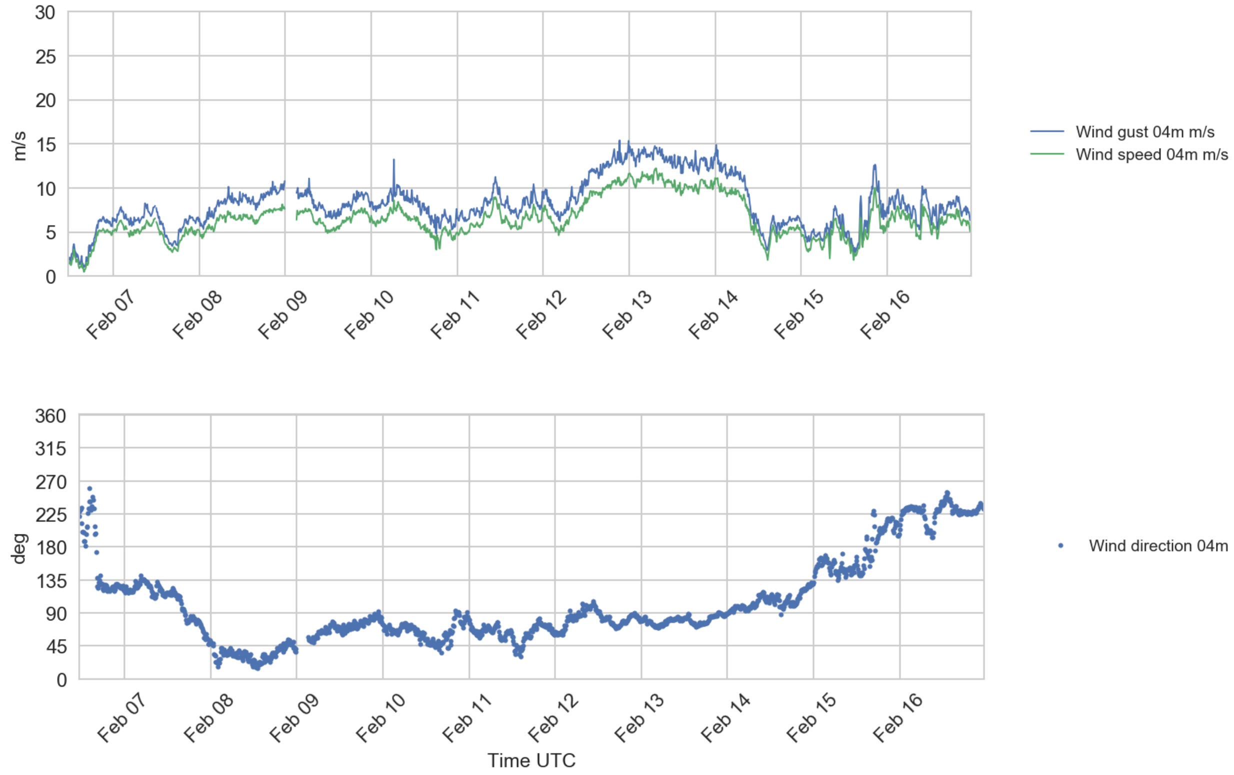

Figure 4.8 Plots of wind speed and gust (upper), and wind direction (lower) at 4 m a.s.l., 6 - 16 Feb 2017.

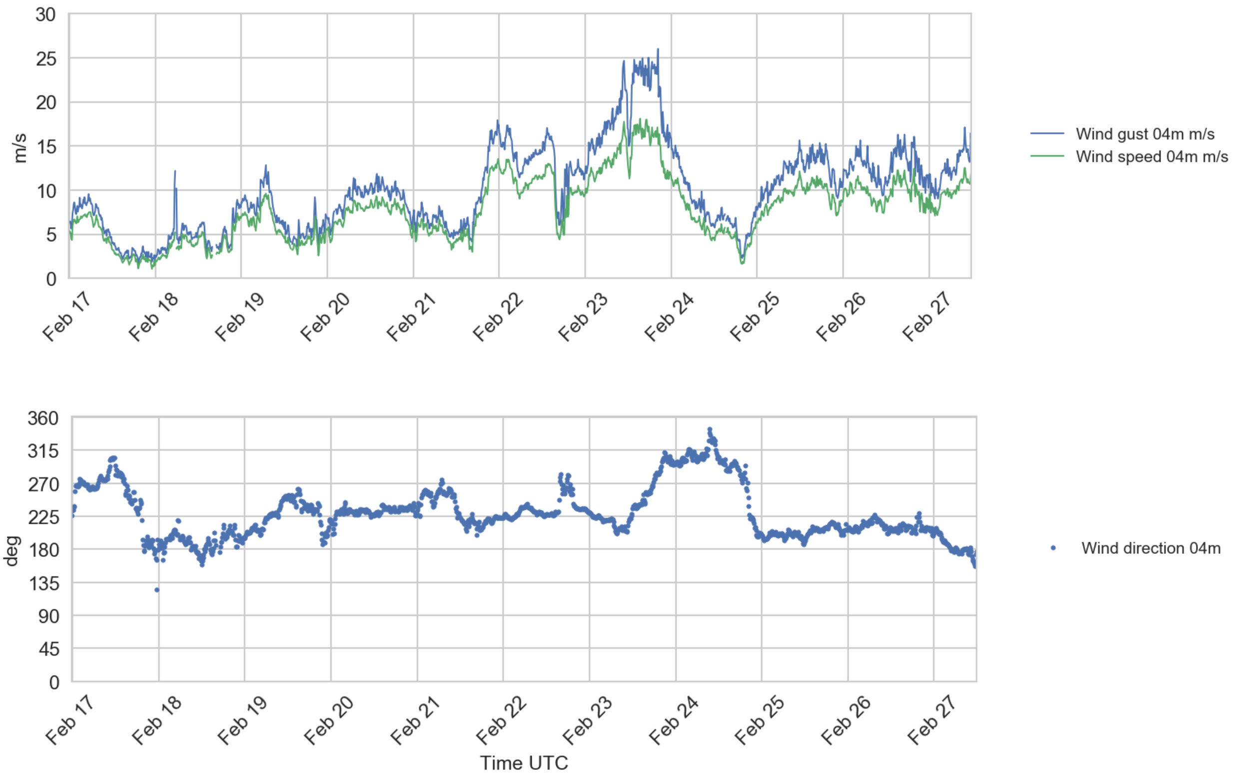

Figure 4.9 Plots of wind speed and gust (upper), and wind direction (lower) at 4 m a.s.l., 16 - 27 Feb 2017.

The wind profiling data from the Lidar are presented in the following plots showing the time series of 10 min. mean wind for each individual level. Plots of the derived parameters Inflow Angle and Turbulence Intensity[3] are also presented.

The Inflow Angle (IA) is the angle of the 3-dimensional wind vector based on the ten minute averaged values of the horizontal and vertical wind velocity components. IA can be positive or negative; a positive IA means that the wind vector has an upward directed vertical component. The Turbulence Intensity (TI) is defined as $TI = \sigma/\bar{u}$ where σ is the standard deviation and $\bar{u}$ is the mean of the wind speed for a 10-min period. Note that this definition frequently gives relatively high values in situations with low but variable wind speed.

The highest observed horizontal mean wind speed during this month varies from 8.8 m/s at 30 m to 11.5 m/s at 200 m above the surface. The maximum winds were measured on 23rd February 2017. The maximum wind speed then varied between 24.7 m/s (at 30 m) to 31.6 m/s (at 200 m). The wind direction was changing from south-west to north-west in that period.

[3] Turbulence Intensity is transmitted using the Iridium Dial-up data transfer mode, separately from the horizontal wind speed, direction and inflow angle which are transmitted as short burst data messages. There are a few gaps in the TI data at times when the dial-up transfer failed, while the wind speed, direction and IA were received normally.

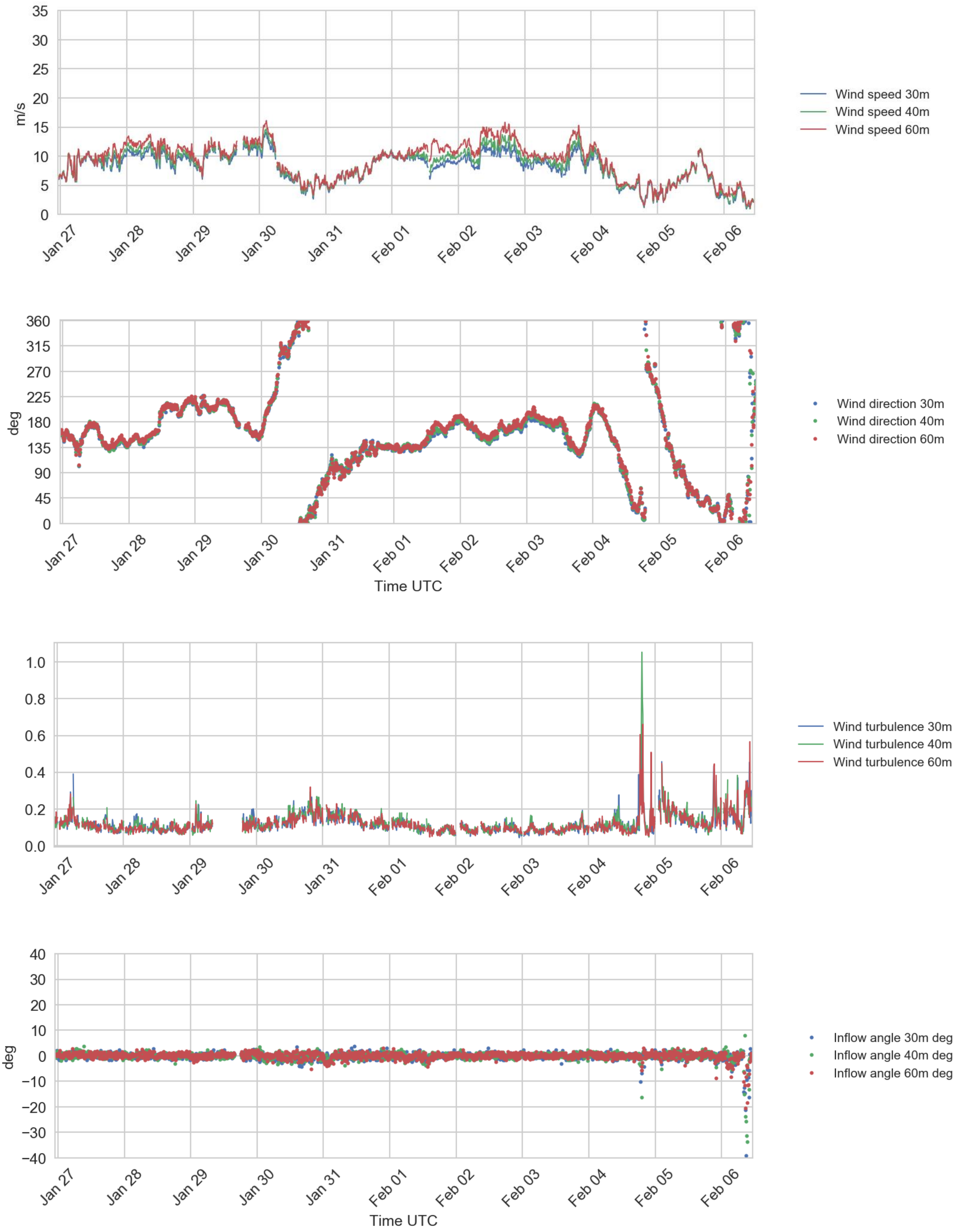

Figure 4.10 Plots of wind profile data, 30 – 60 m a.s.l., 26 Jan - 6 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

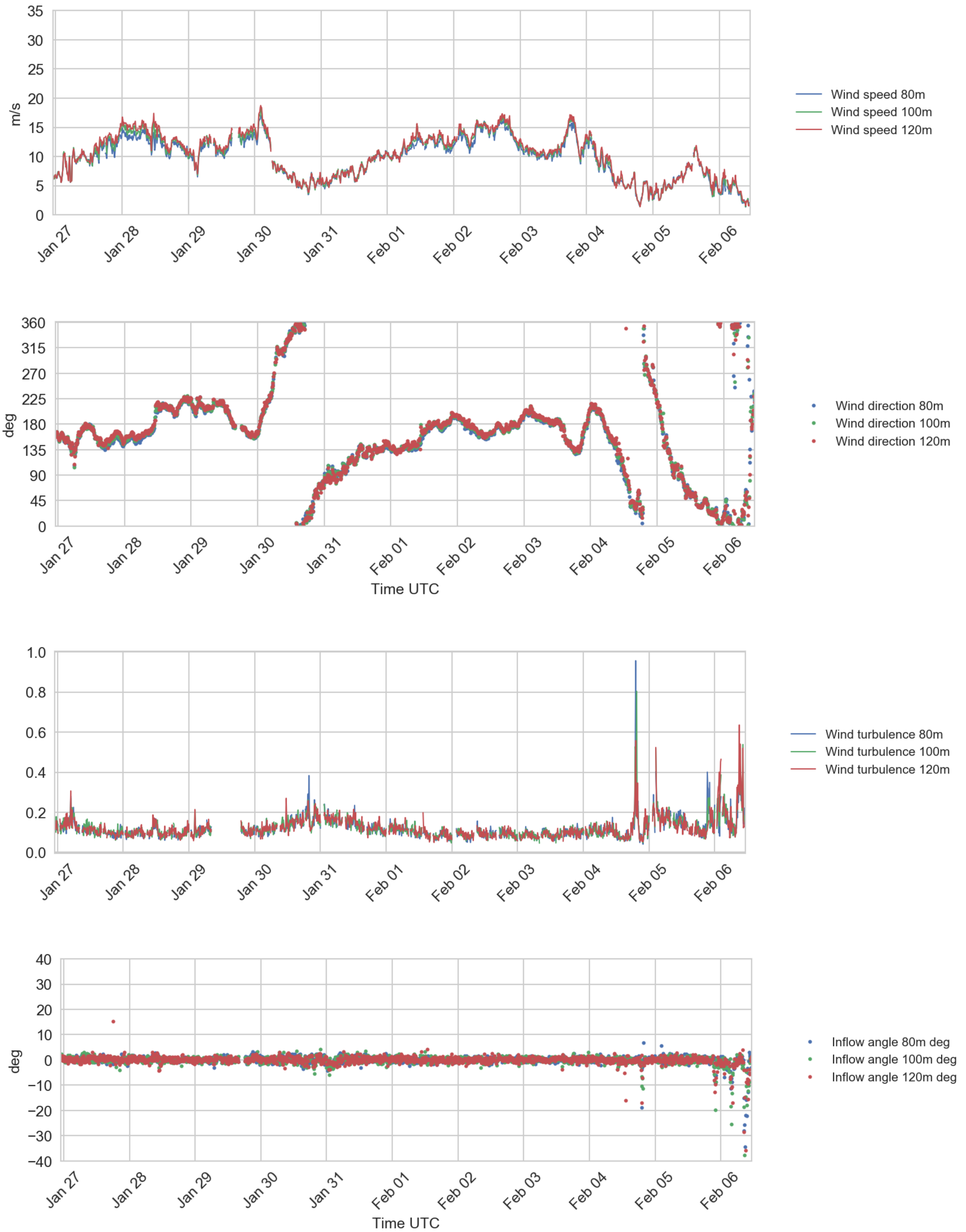

Figure 4.11 Plots of wind profile data, 80 – 120 m a.s.l., 26 Jan - 6 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

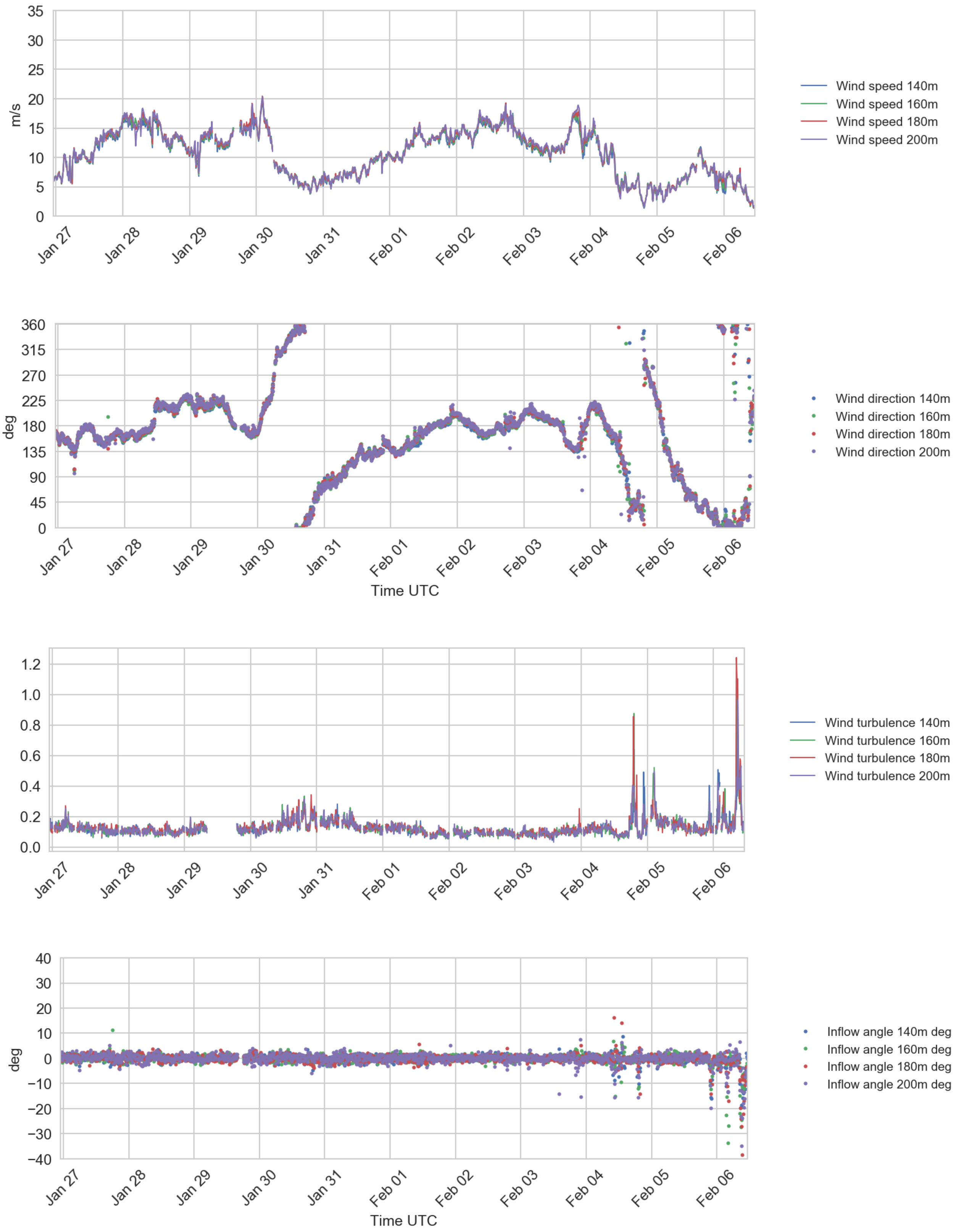

Figure 4.12 Plots of wind profile data, 140 – 200 m a.s.l., 26 Jan - 6 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

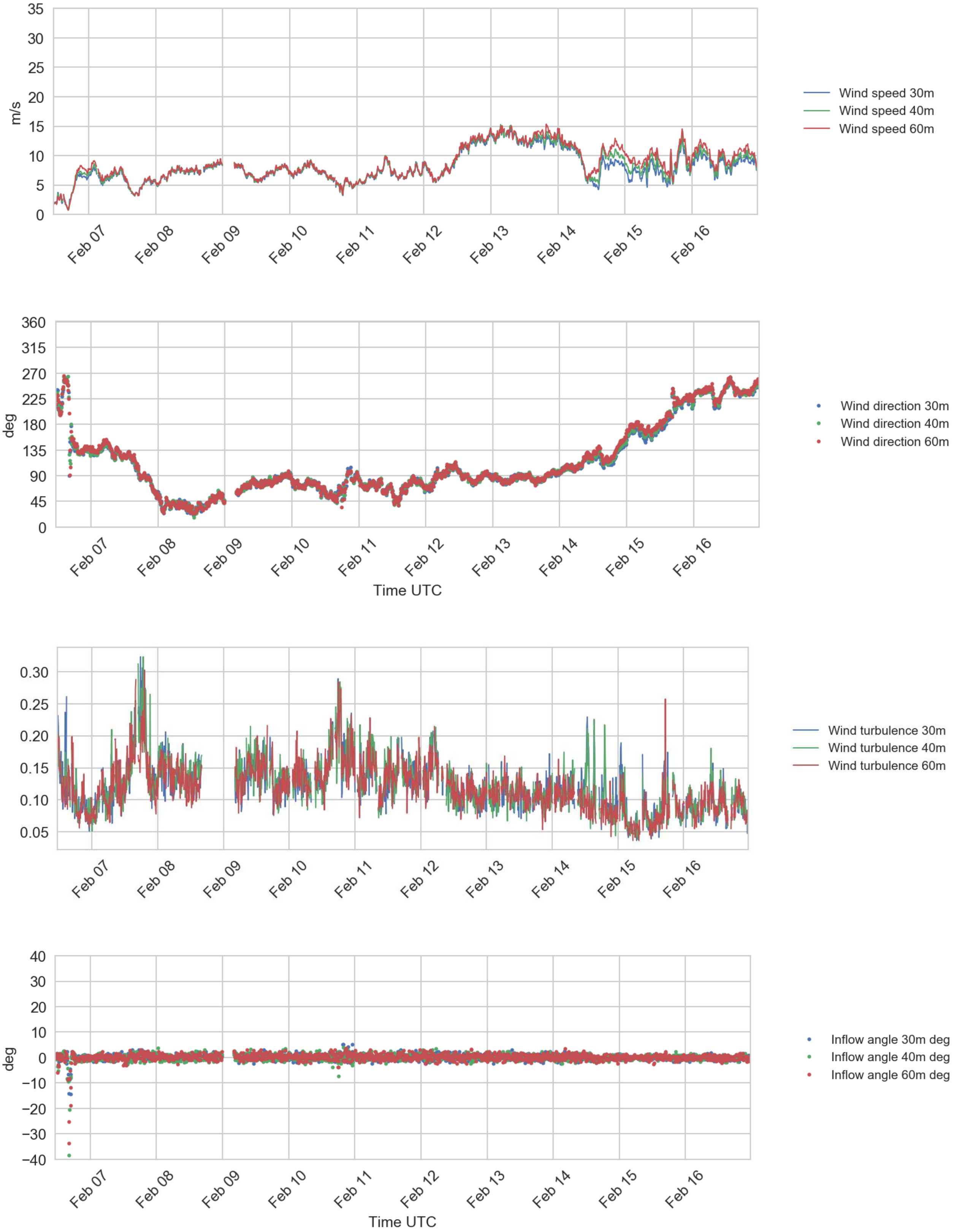

Figure 4.13 Plots of wind profile data, 30 – 60 m a.s.l., 6 - 16 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

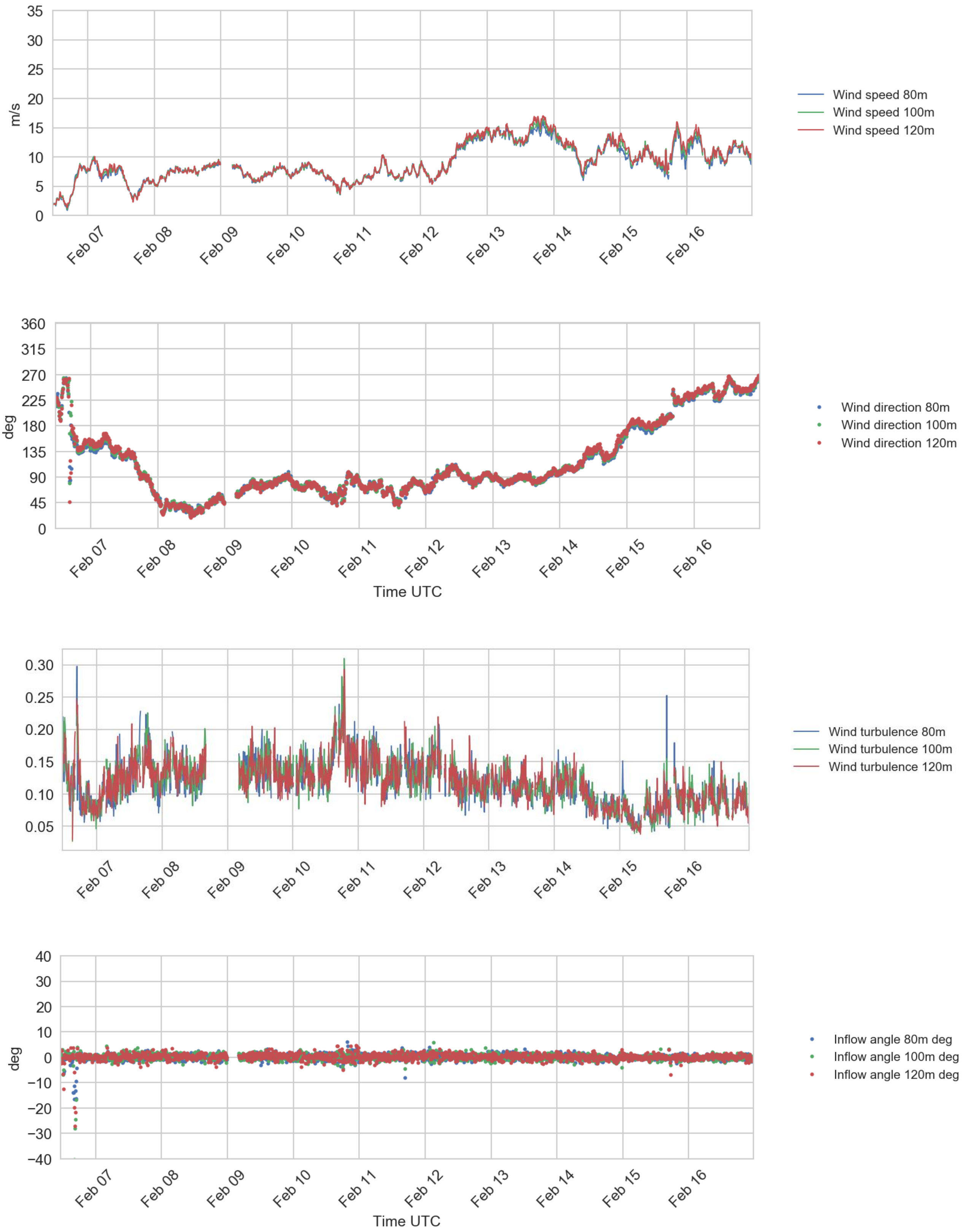

Figure 4.14 Plots of wind profile data, 80 – 120 m a.s.l., 6 - 16 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

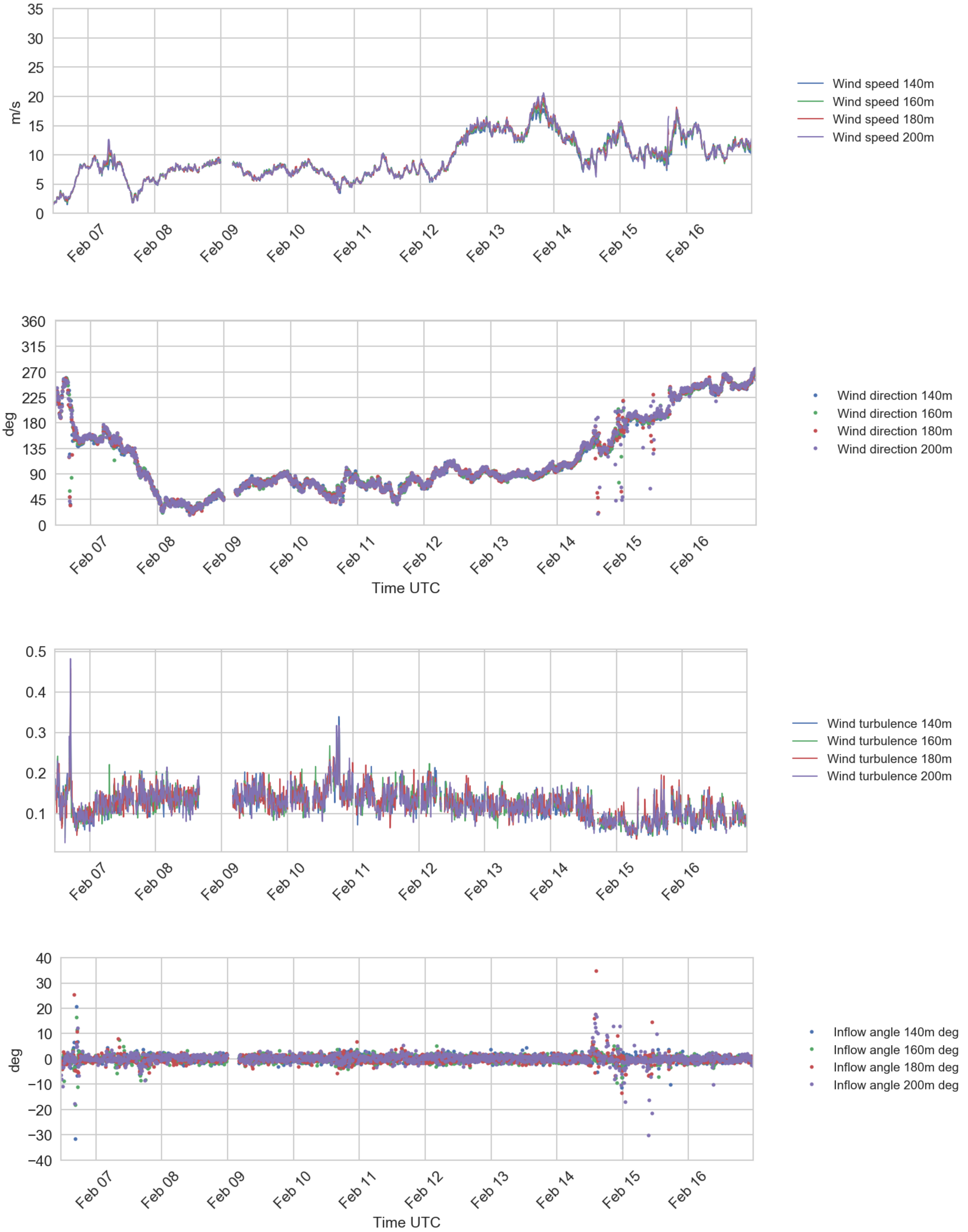

Figure 4.15 Plots of wind profile data, 140 – 200 m a.s.l., 6 - 16 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

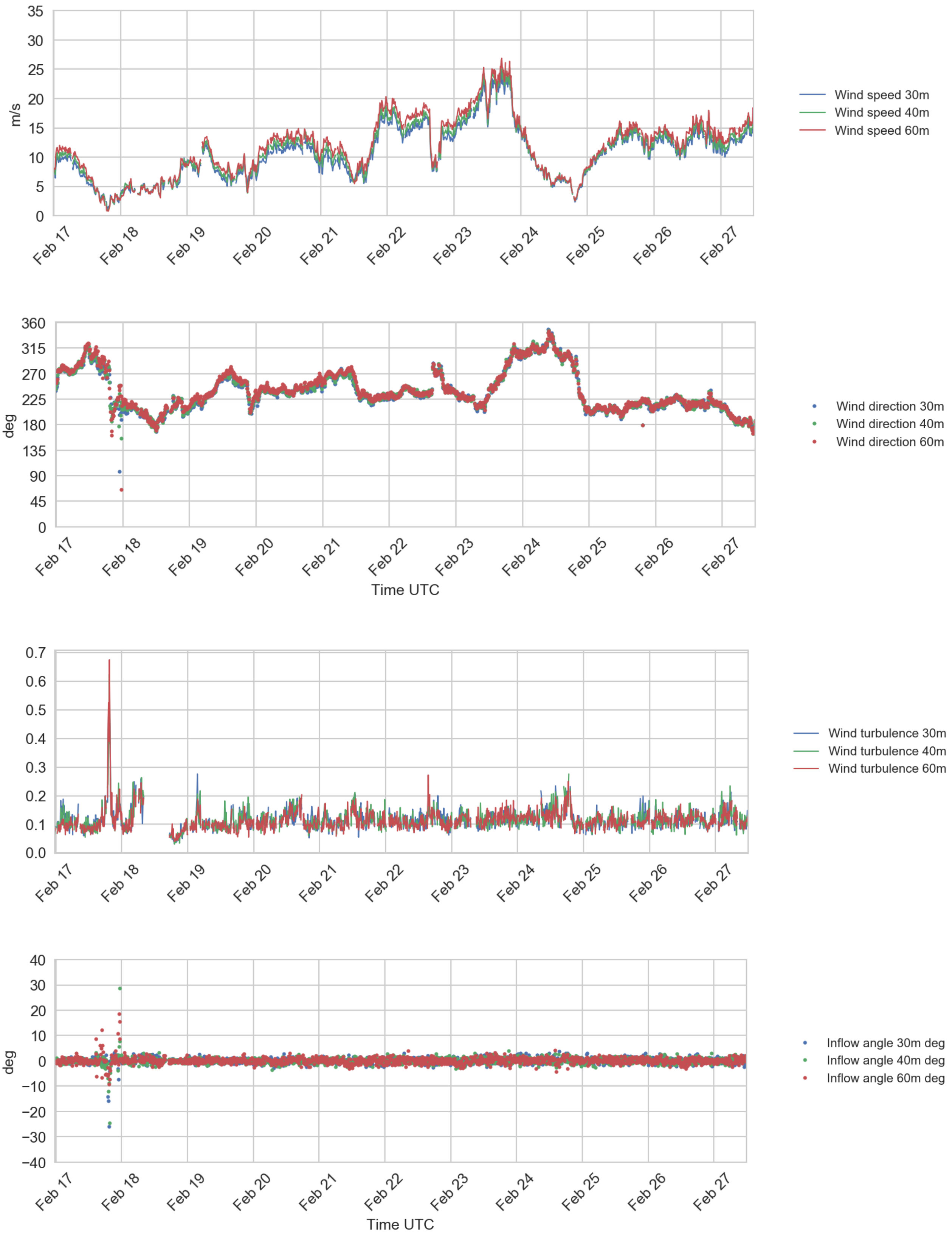

Figure 4.16 Plots of wind profile data, 30 – 60 m a.s.l., 16 - 27 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

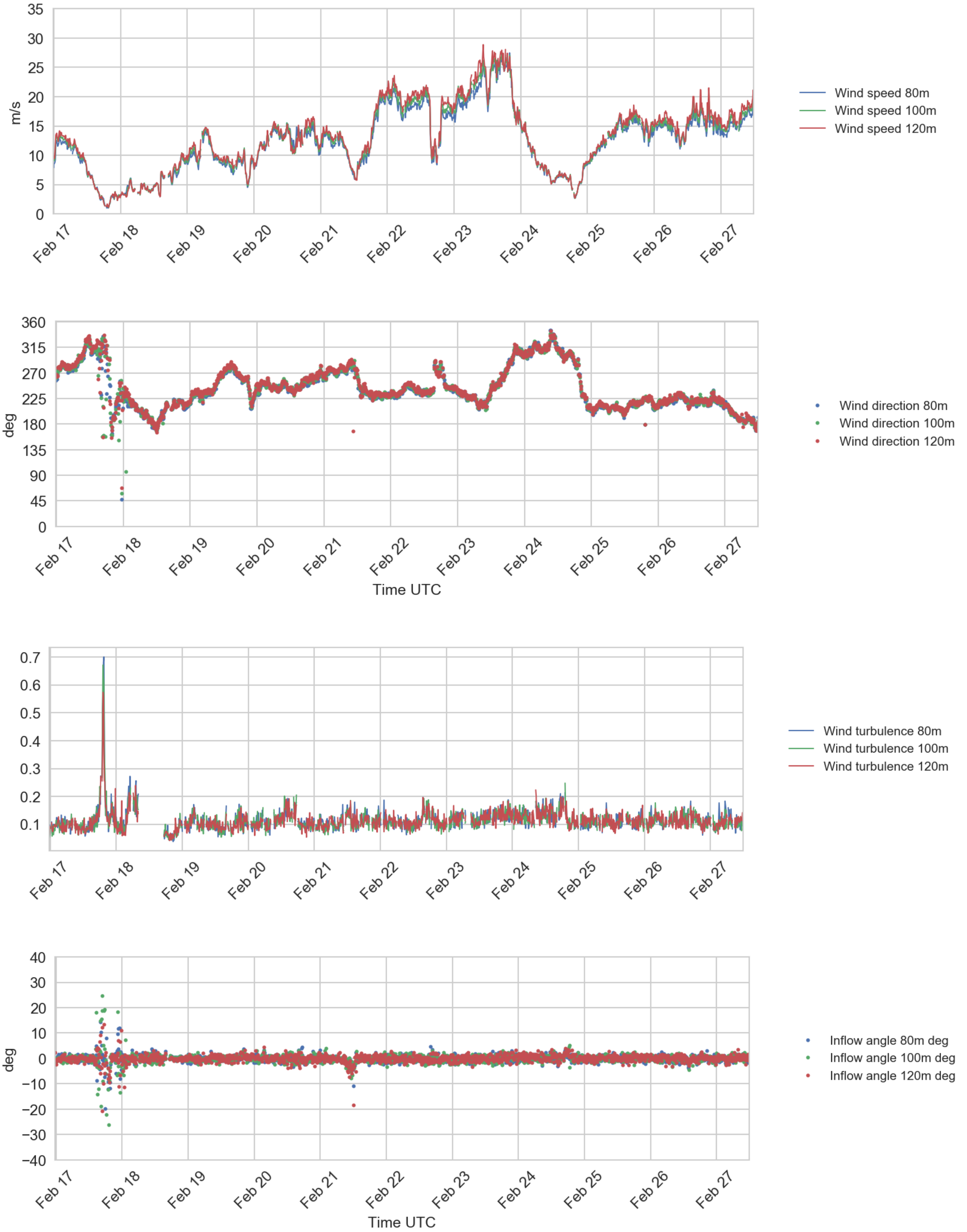

Figure 4.17 Plots of wind profile data, 80 – 120 m a.s.l., 16 - 27 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

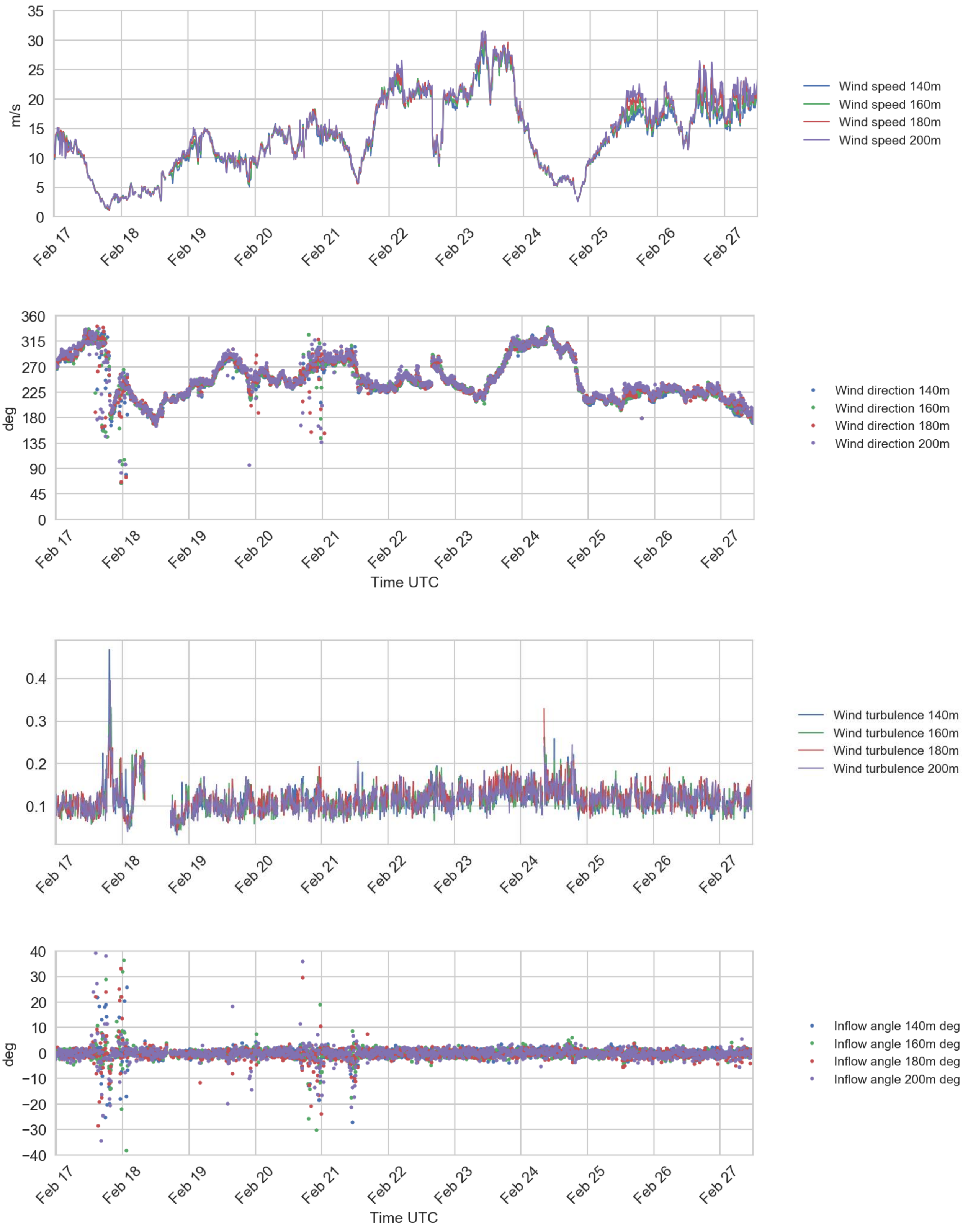

Figure 4.18 Plots of wind profile data, 140 – 200 m a.s.l., 16 - 27 Feb 2017.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

4.2.4 Current velocity profile data

The following plots show the current velocity profile time series. In these plots current direction 0° or 360° means that the current flows toward north, 90° indicates flow toward east etc. In general the current profiler has worked well, just a few data points were lost due to buoy restarting, but otherwise the series is continuous.

As expected for this location the current velocity data show a very strong and consistent semi-diurnal tidal current pattern, completing two full rotations of the current vector per day, and four tidal current maxima; two toward south-southwest and two toward north-east. This clear, strong and consistent semi-diurnal pattern in current velocity with two peaks per day is strong evidence that the current sensor produces correct and good data.

The quarter-diurnal peaks in the tidal current speed normally vary between 60 – 100 cm/s over the month, depending on the phases of the moon. The average current speed shows little variation in the profile above the bottom layer; from around 51 cm/s between 6 – 16 m below surface to 45 cm/s at 26 m depth. The maximum observed current speed was 102 cm/s toward South West (220°) at 8 m depth on 12th of February.

At the lowest level, 30 m and, possibly, 28 m depth, the current speeds are reduced when the profiling beam hits the bottom. This usually occurs at every other peak in the current speed; that is when the strong current coincides with low tide.

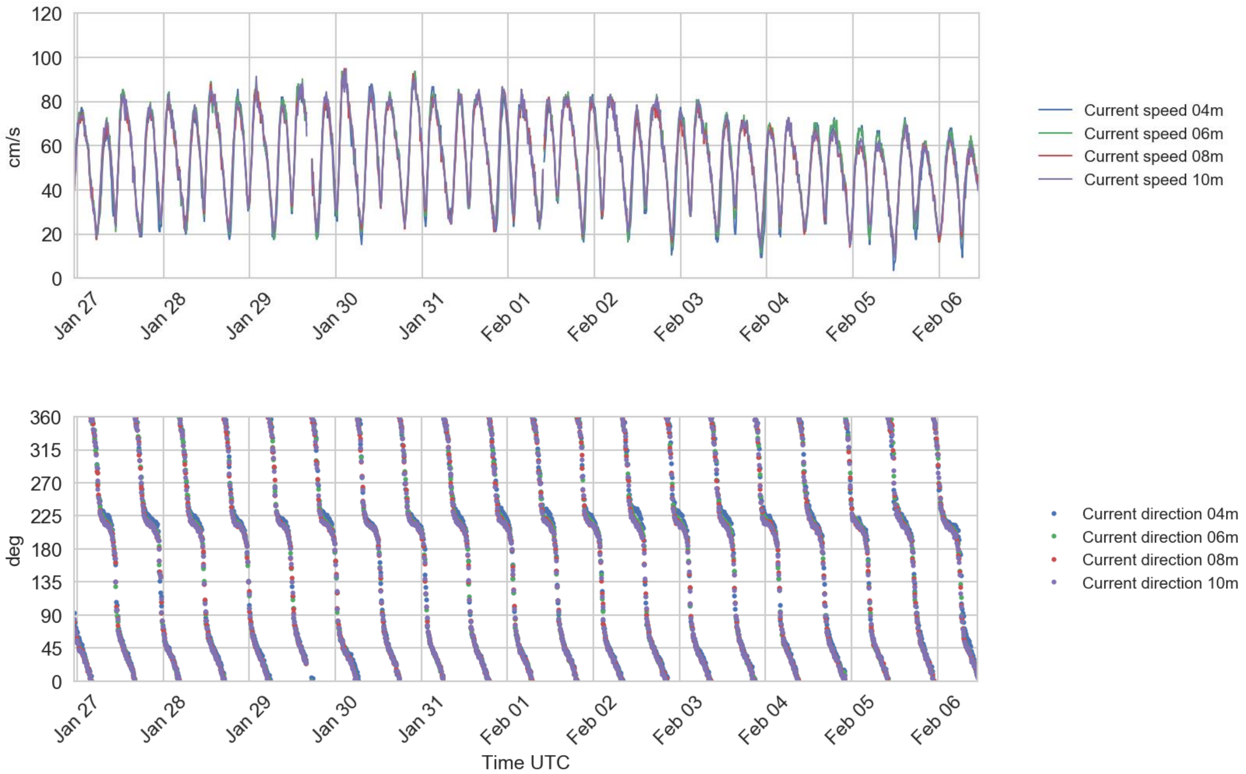

Figure 4.19 Time series plots of current speed (upper) and direction (lower panel), 4 - 10 m depth, 26 Jan - 6 Feb 2017.

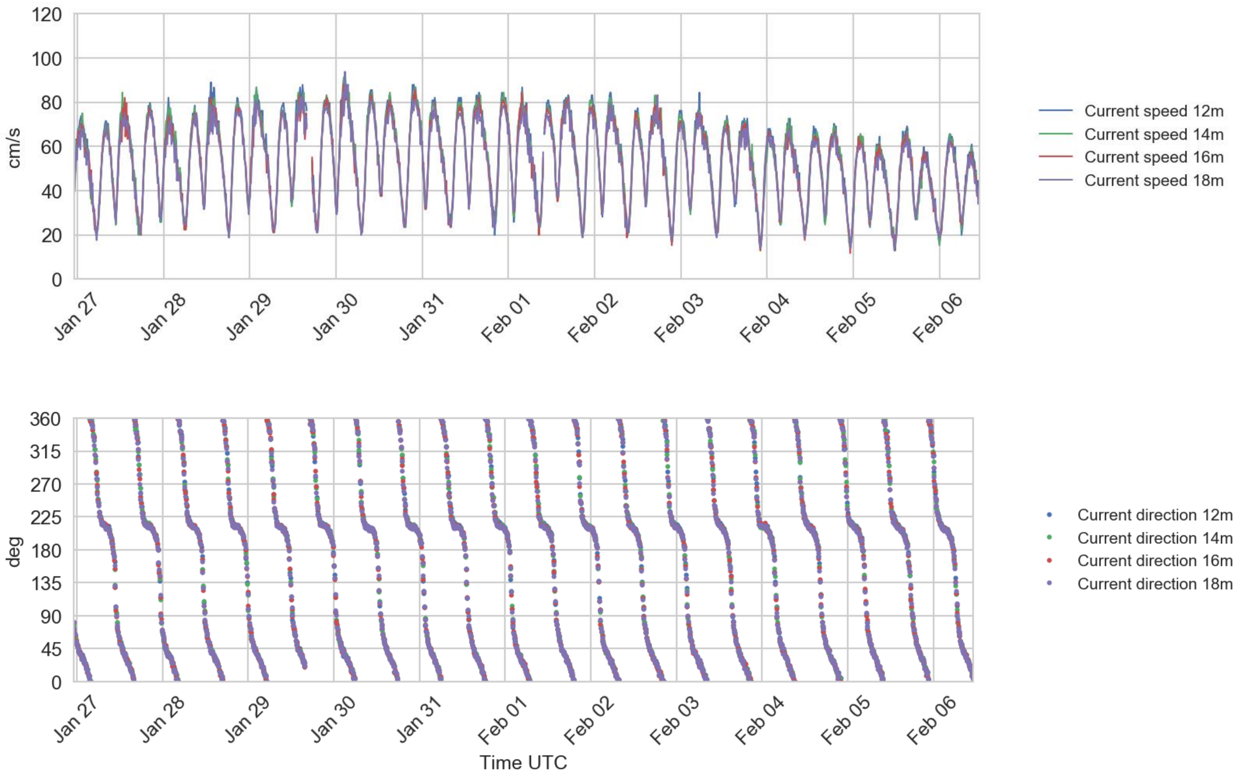

Figure 4.20 Time series plots of current speed (upper) and direction (lower panel), 12 - 18 m depth, 26 Jan - 6 Feb 2017.

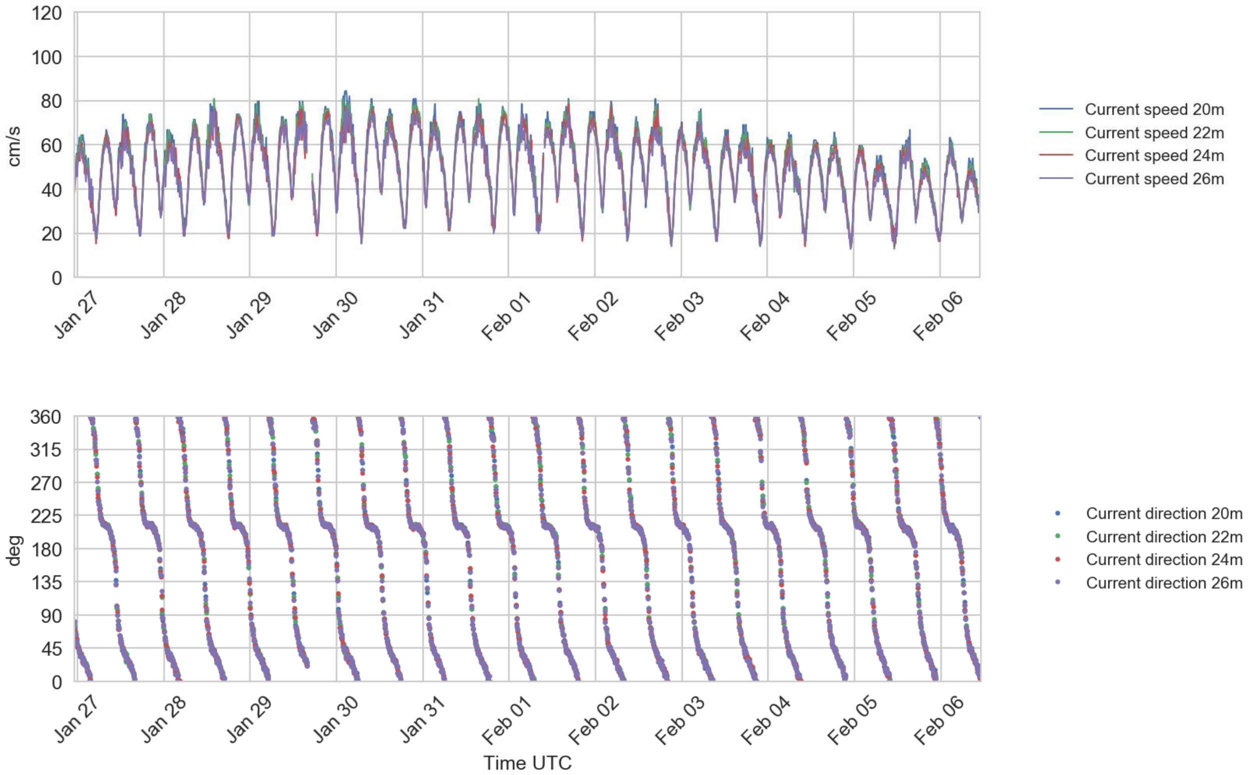

Figure 4.21 Time series plots of current speed (upper) and direction (lower panel), 20 - 26 m depth, 26 Jan - 6 Feb 2017.

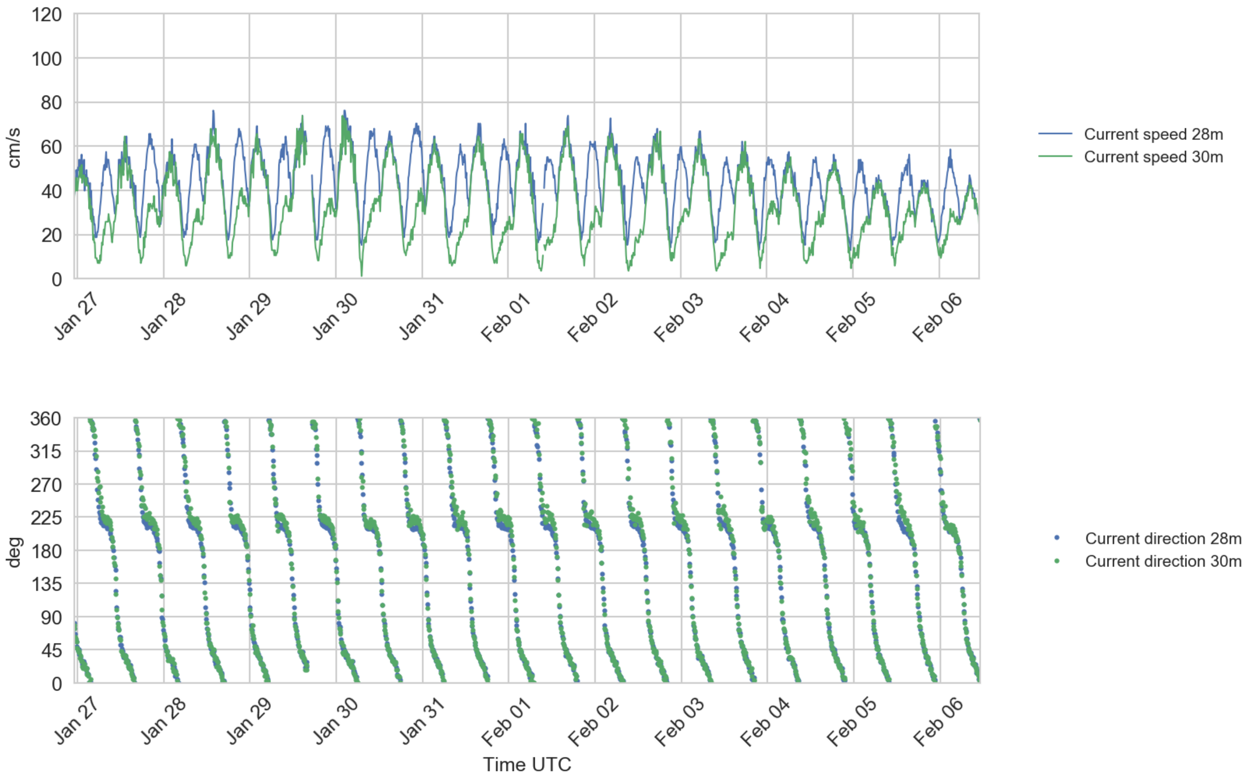

Figure 4.22 Time series plots of current speed (upper) and direction (lower panel), 28 - 30 m depth, 26 Jan - 6 Feb 2017.

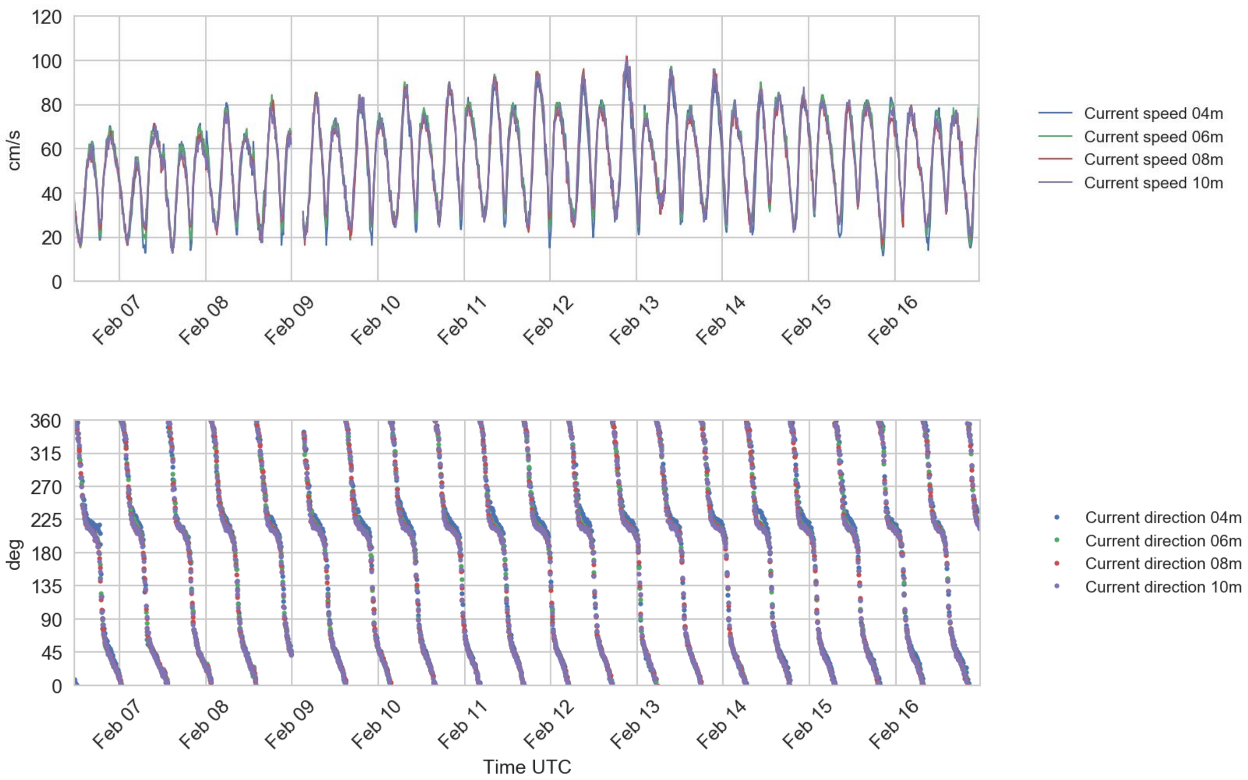

Figure 4.23 Time series plots of current speed (upper) and direction (lower panel), 4 - 10 m depth, 6 - 16 Feb 2017.

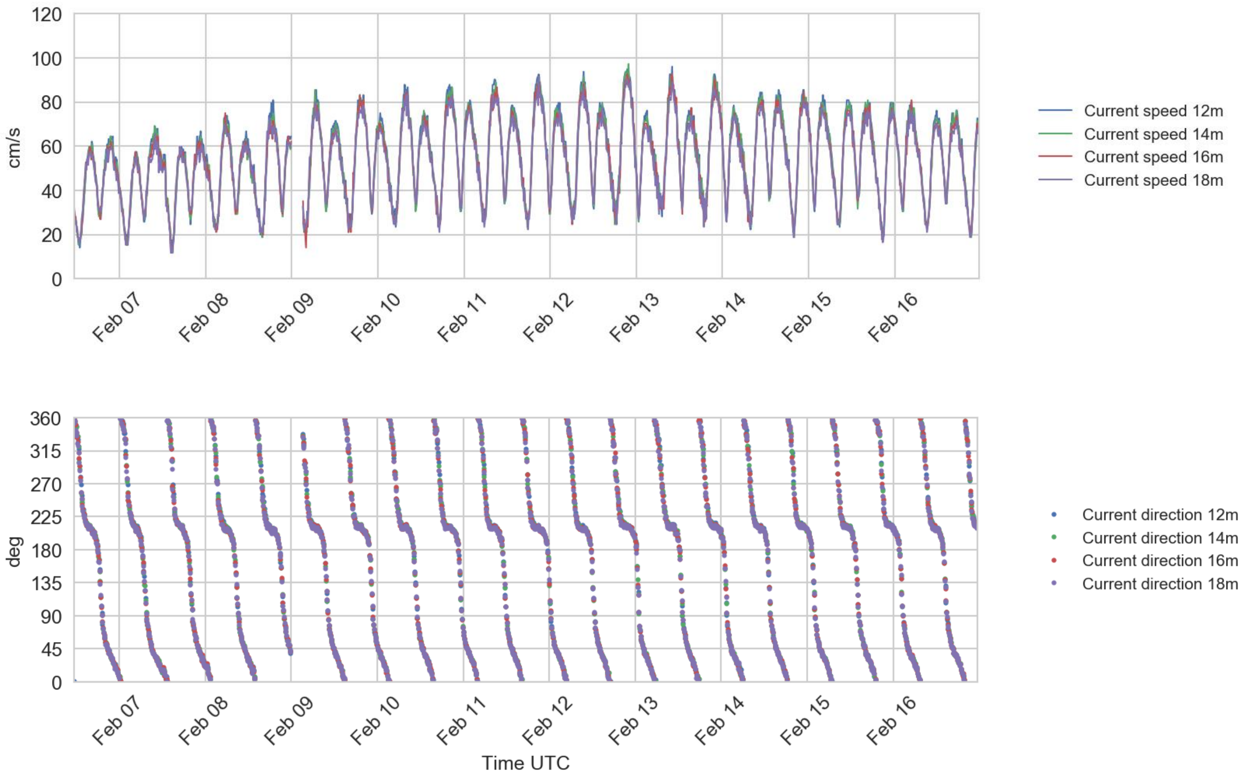

Figure 4.24 Time series plots of current speed (upper) and direction (lower panel), 12 -18 m depth, 6 - 16 Feb 2017.

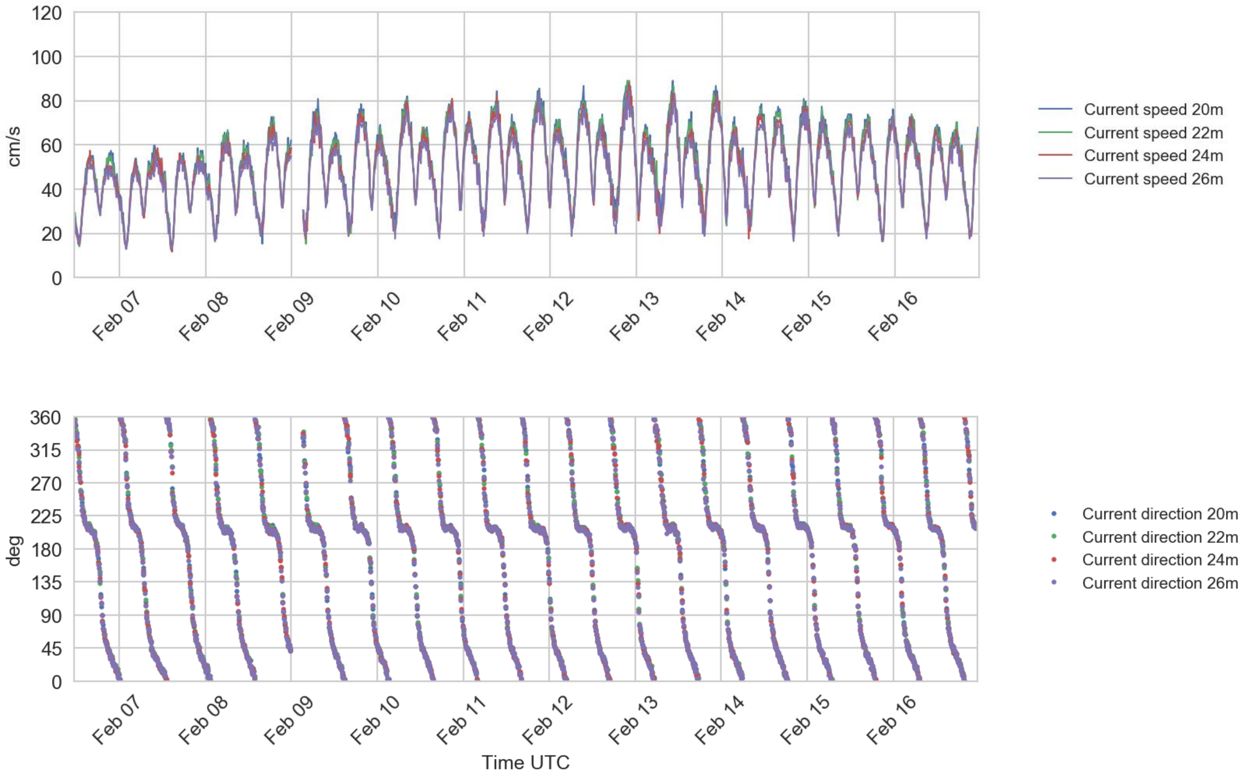

Figure 4.25 Time series plots of current speed (upper) and direction (lower panel), 20 – 26 m depth, 6 - 16 Feb 2017.

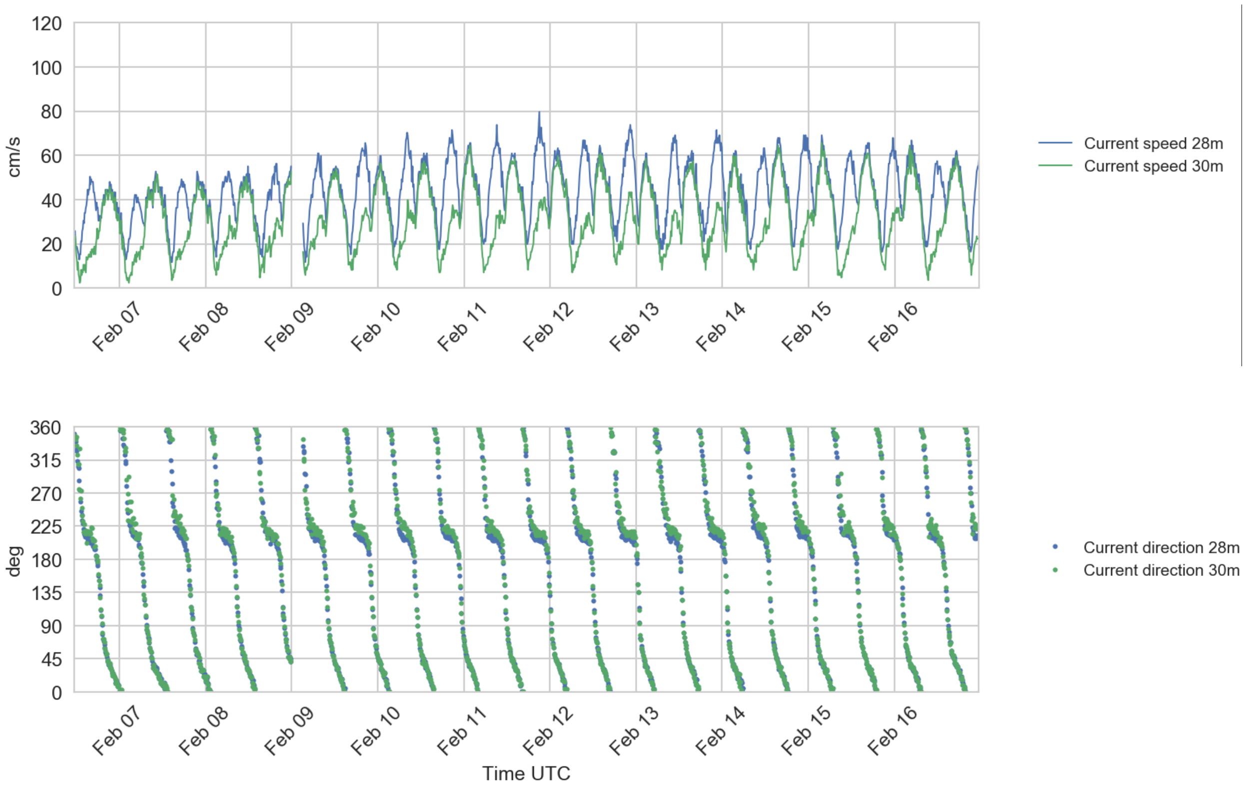

Figure 4.26 Time series plots of current speed (upper) and direction (lower panel), 28 – 30 m depth, 6 - 16 Feb 2017.

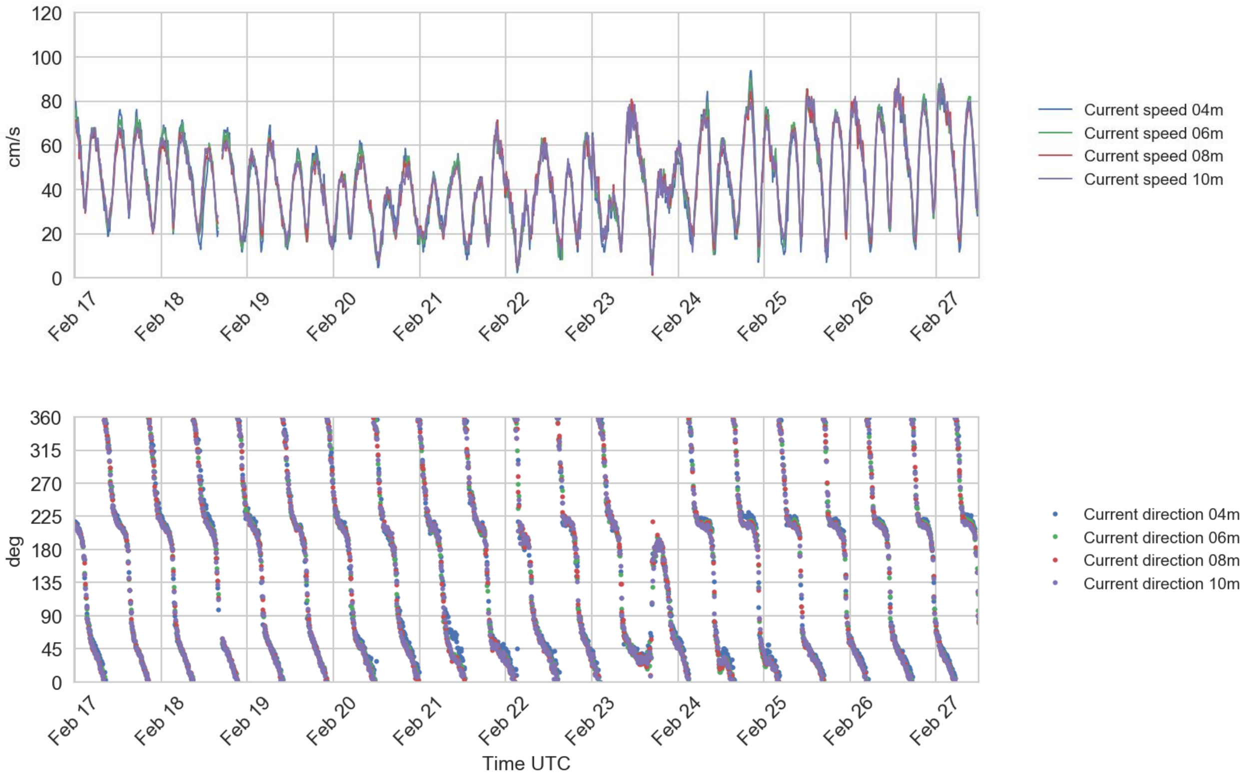

Figure 4.27 Time series plots of current speed (upper) and direction (lower panel), 4 - 10 m depth, 16 - 27 Feb 2017.

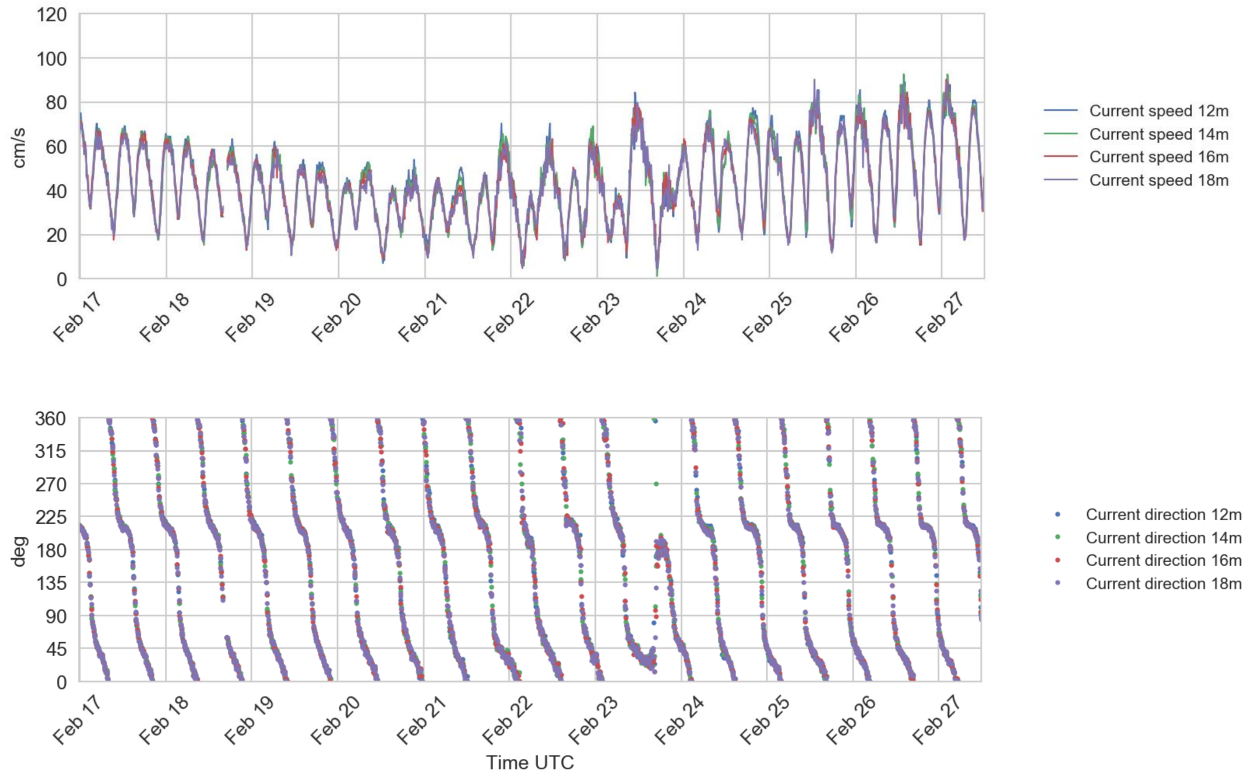

Figure 4.28 Time series plots of current speed (upper) and direction (lower panel), 12 - 18 m depth, 16 - 27 Feb 2017.

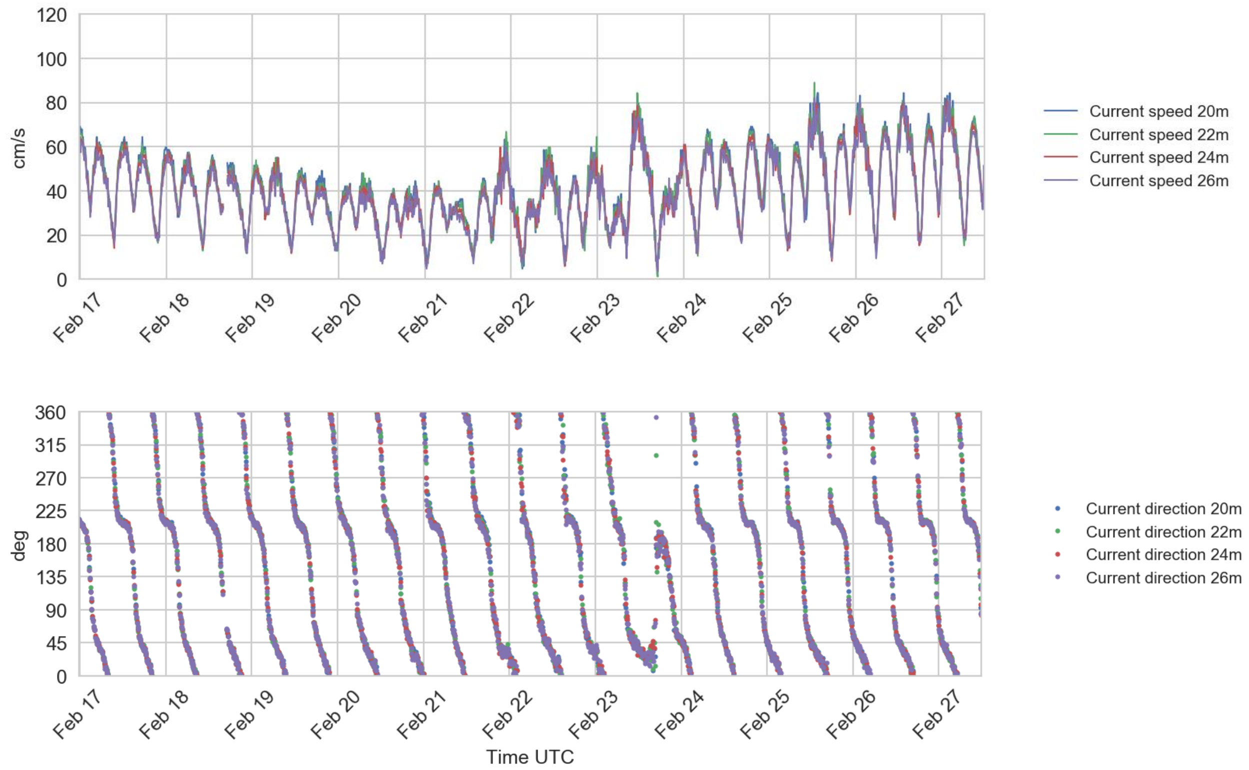

Figure 4.29 Time series plots of current speed (upper) and direction (lower panel), 20 - 26 m depth, 16 - 27 Feb 2017.

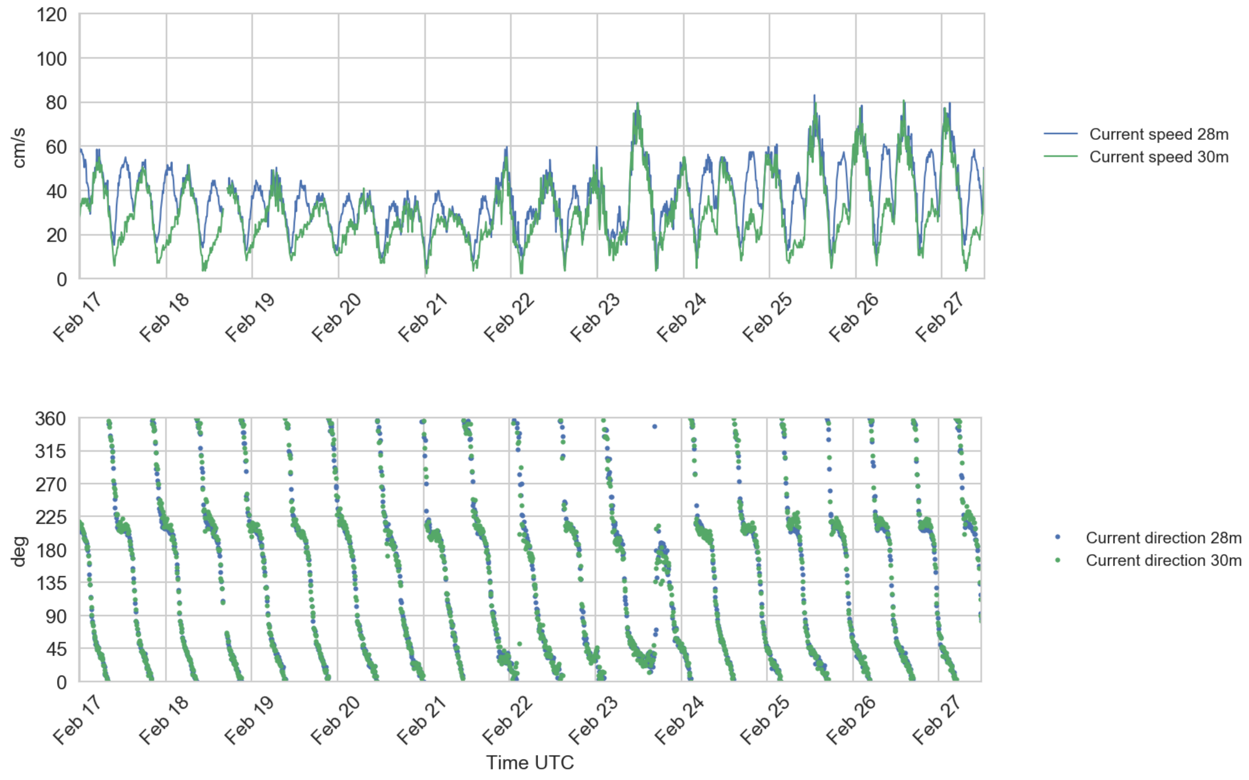

Figure 4.30 Time series plots of current speed (upper) and direction (lower panel), 28 - 30 m depth, 16 - 27 Feb 2017.

During 23-24 February the current direction pattern deviates from the regular pattern, i.e. there are very few measurements between 200^o and 360^o. Also the current speed pattern deviates from the regular, i.e. two narrow peak in current has merged into one wider. This is the time when max wind speed and max waves were measured, see figure 4.6, 4.9 and 4.16. The storm was strong enough to withstand one tidal cycle and forced it in the direction opposite of the regular.

4.2.5 Water level and bottom temperature data

The buoy received no data from the bottom mounted Seaguard WLR via the acoustic data link during this month. The previously received data indicate that the communication link between the sensor and the buoy was broken on 8 July 2015. The data can be recovered from the internal storage in the WLR when it is recovered from the seabed.

Several attempts to recover the WLR have been performed without success. It is thus decided to postpone further attempts until better weather and lighter days come in the spring.

Since data recovery is of major importance, a second WLR recorder was deployed on 18 December 2015 together with the buoy to ensure data recovery. Due to long delivery times a spare acoustic communication system was not available at that time, and it was decided to deploy a WLR without the acoustics to ensure recovery of water level data. At least one of the two WLR units will record data that can be recovered from the seabed later.

Appendix A Deployment sheet

Appendix B DEPLOYMENT/RECOVERY SHEET				
Project Name: Borselle				
Project no: C75339	Latitude: 51°42.41388'N (x=502392)			
Station name: Borselle Lot 1	Longitude: 3°2.07708'E (y=5728440)			
WS buoy no: WS157	Approx. depth: 30m			
PFF numbers:	Buoy marking: YES			
Buoy module/sensor	**Serial number/ID**			
CONFIGURATION				
Data transmission interval:				
Listening window				
POWER OPTIONS				
Lead batteries type				
DEPLOYMENT HISTORY				
	YEAR	**MONTH**	**DATE**	**GMT**
First measurement	2016	February	12	1200
First measurement this deployment	2016	December	12	1205
Out of measuring position				
Last measurement				
Comments: WS157 attatched to the Borselle Lot 1 mooring.				
WS157 deployment vessel: Multrasalvor 3	WS157 deployed by: Lars Slettemark			

THE NETHERLANDS ENTERPRISE AGENCY (RVO)

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ)
Validation report: 26 January - 27 February 2017

Reference No: C75339_VAL16_R1
31 March 2017

Fugro Norway AS
OCEANOR, Pirsenteret, P.O. Box 1224, Sluppen, N-7462 Trondheim, Norway
Tel: +47 73545200 Fax: +47 73545201, e-mail: trondheim@oceanor.com

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ): C75339_VAL16_R1				
Rev	**Date**	**Originator**	**Checked & Approved**	**Issue Purpose**
0	03.03.2017	Ola Storås	Arve Berg	Draft report
1	31.03.2017	Ola Storås	Arve Berg	Final report

Rev 1 – 31 March 2017	**Originator**	**Checked & Approved**
Signed:		

This report is not to be used for contractual or engineering purposes unless the above is signed where indicated by both the originator of the report and the checker/approver and the report is designated 'FINAL'.

TABLE OF CONTENT

SUMMARY

The Seawatch Wind Lidar buoy is deployed at the Borssele Wind Farm Zone (BWFZ). The buoy was first deployed on 11 June 2015 at 15:55 UTC, and a bottom mounted tide gauge (WLR) was deployed at 16:15 UTC on the same day. This report presents an evaluation of the wind and wave data collected during the period 26 January - 27 February 2017, comparing the buoy data to data from two fixed measurement stations in the region.

In total 3 different buoys has been used for the measurements. In the whole 2015 and until 19th January 2016 the Seawatch Wind Lidar buoy WS149 was used for the measurements. On the 12th February 2016 the SW Wind Lidar buoy WS157 was deployed at the same position. This buoy was used for the measurements until 20th July 2016 and was then swapped with SW Wind Lidar buoy WS156. Buoy WS156 was then used until 12th December 2016 when it was swapped with SW Wind Lidar buoy WS157.

The reference station for comparing wave measurements is a Waverider buoy at Schouwenbank (station SCHB), and the reference for wind measurements is the platform at Vlakte van de Raan (VR).

Although the reference stations are some 19 – 26 km away from the buoy location we see good agreement between the buoy and references. The waves this month has been lower and shorter than previous months and this will lead to more scatter (lower R^2) when wave height and period are compare over some distance.

1. INTRODUCTION

A Seawatch Wind Lidar buoy is deployed at the Borssele Wind Farm Zone (BWFZ) in the Dutch sector of the North Sea. The buoy with serial no WS149 was first deployed on 11 June 2015 at 15:55 UTC with the bottom mooring weight at position 51° 42.41388' N, 3° 2.07708' E. A bottom mounted water level recorder (WLR) at position 51° 42.4362' N, 3° 02.1030' E transmits data to the buoy in real time data via an acoustic link. The water depth at this location is approximately 30 m.

In total 3 different buoys has been used for the measurements. In the whole 2015 and until 19th January 2016 the Seawatch Wind Lidar buoy WS149 was used for the measurements. The Lidar on Buoy WS149 stopped working on 26 December 2015 due to a technical problem with its Lidar power switch. After a long period of unworkable weather conditions, and some delay due to vessel unavailability, the buoy was recovered for repair on 19 January 2016. The root cause of the problem was found and measures were taken to prevent it from happen again.

On the 12th February 2016 the SW Wind Lidar buoy WS157 was deployed at the same position at 13:00. This buoy was in successful operation in position until recovery for fuel refill on 20th July 2016 and was then swapped with SW Wind Lidar buoy WS156 at 10:00 UTC. This buoy was then used until 12th December 2016 when it was swapped with SW Wind Lidar buoy WS157. All the buoys used have been pre-deployment validated at Fugro OCEANOR test site according to the Carbon Trust OWA roadmap, approved by DNV-GL (reports are published on RVO web page for offshore wind).

Data collected during the period 26 January - 27 February 2017 are presented in the data presentation report ref. C75339_MPR16_R1.

This report presents an evaluation of the wind and wave data collected in the period 26 January - 27 February 2017, comparing the buoy data to data from fixed measurement stations in the area. The reference stations used in this report are the Waverider buoy at Schouwenbank (station SCHB) for waves, and a platform with a wind sensor at Vlakte van de Raan (VR) for wind measurements. The comparisons are shown in time series and scatter plots.

The time reference used in this report is UTC.

2. Instrumentation and measurement configuration

The buoy is a Seawatch Wind Lidar Buoy based on the original Seawatch Wavescan buoy design with the following sensors:

- Wavesense: 3-directional wave sensor
- Xsens 3-axes motion sensor
- Gill Windsonic M acoustic wind sensor
- Vaisala PTB330A air pressure sensor
- Vaisala HMP155 air temperature and humidity sensor
- Nortek Aquadopp 600kHz current profiler.
- ZephIR 300S Lidar.

An independent self-recording Aanderaa SeaGuard WLR tide gauge is located on the bottom. The WLR transmits data to the buoy via an acoustic link.

The buoy with mooring as deployed is presented in Figure 2.1, including the mooring for the WLR.

The measurement setup is detailed in Table 2.1. Detail information such as sensor types and serial numbers can be found in the deployment record in Appendix A.

Table 2.1 Configuration of measurements by the Seawatch Wind Lidar buoy at Borssele Borssele Wind Farm Zone (BWFZ).

Instrument type	Sensor height (m)	Parameter measured	Sample height[2)] (m)	Sampling interval (s)	Averaging period (s)	Burst interval (s)	Trans-mitted?
Wavesense 3	0	Heave, pitch, roll, heading	0	0.5	Time series duration: 1024 s	600	No
		Sea state parameters (1)	0	600	1024	600	Yes
Xsens		Heave,east,north acceleration, q0,q1,q2,q3 (attitude quaternion)	0	0.5	N/A	3600	No
Gill Windsonic M	4.1	Wind speed, wind direction	4.1	1	600	600	Yes
Vaisala PTB330A	0.5	Air pressure	0.5	30	60	600	Yes
Vaisala HMP155	4.1	Air temperature Air humidity	4.1	5	60	600	Yes
Nortek Aquadopp	-1	Current speed and direction profile, water temperature (at 1 m depth)	-4 -6 … -30 (14 levels)	N/A	600	600	Yes
ZephIR 300S Lidar	2	Wind speed and direction at 10 heights (The 11th level, the so called reference level which is not configurable, is also located at 40 m and referred to as 40.0 Ref.)	30.0 40.0 40.0 ref 60.0 80.0 100.0 120.0 140.0 160.0 180.0 200.0	≈ 17.4 s[1)]	600	600	Yes
Aanderaa WLR (SeaGuard) via acoustic link	-30	Water pressure Temperature	-30	600	60	600	Yes[3)]

1) This is the approximate time between the beginning of one sweep of the profile and the next one, the interval may vary slightly. The ZephIR sweeps one level at a time beginning at the lowest one, and after the top level has been swept it uses some time for calculations and re-focusing back to the lowest level for a new sweep.
2) Height relative to actual sea surface. The depth of the WLR is an approximate number.
3) The WLR data are not transmitted after 8 July 2015 due to failure of the acoustic link. An additional self-contained WLR was deployed 18 December 2015 to ensure data recovery.

Table 2.2 Definitions of wave parameters presented in this report

H	Individual wave height
Hmax	= Max(H): Height of the highest individual wave in the sample, measured from crest to trough
m0, m1, m2, m4, m-1, m-2	Moments of the spectrum about the origin: $\int f^k S(f)df$ where $S(f)$ is the spectral density and the wave frequency, f, is in the range 0.04 - 0.50 Hz
Hm0	Estimate of significant wave height, Hs, $Hm0 = 4\sqrt{m0}$
Tp	Period of spectral peak = $1/f_p$, The frequency/period with the highest energy
Tm01	Estimate of the average wave period; $Tm01 = m0/m1$
Tm02	Another estimate of the average wave period; $Tm02 = \sqrt{\frac{m0}{m2}}$
ThTp	Mean wave direction at the spectral peak ("The direction of most energetic waves")
Mdir	Wave direction averaged over the whole spectrum
	Directions are given in degrees clockwise from north, giving the direction the waves come from. (0° from north, 90° from east, etc.)

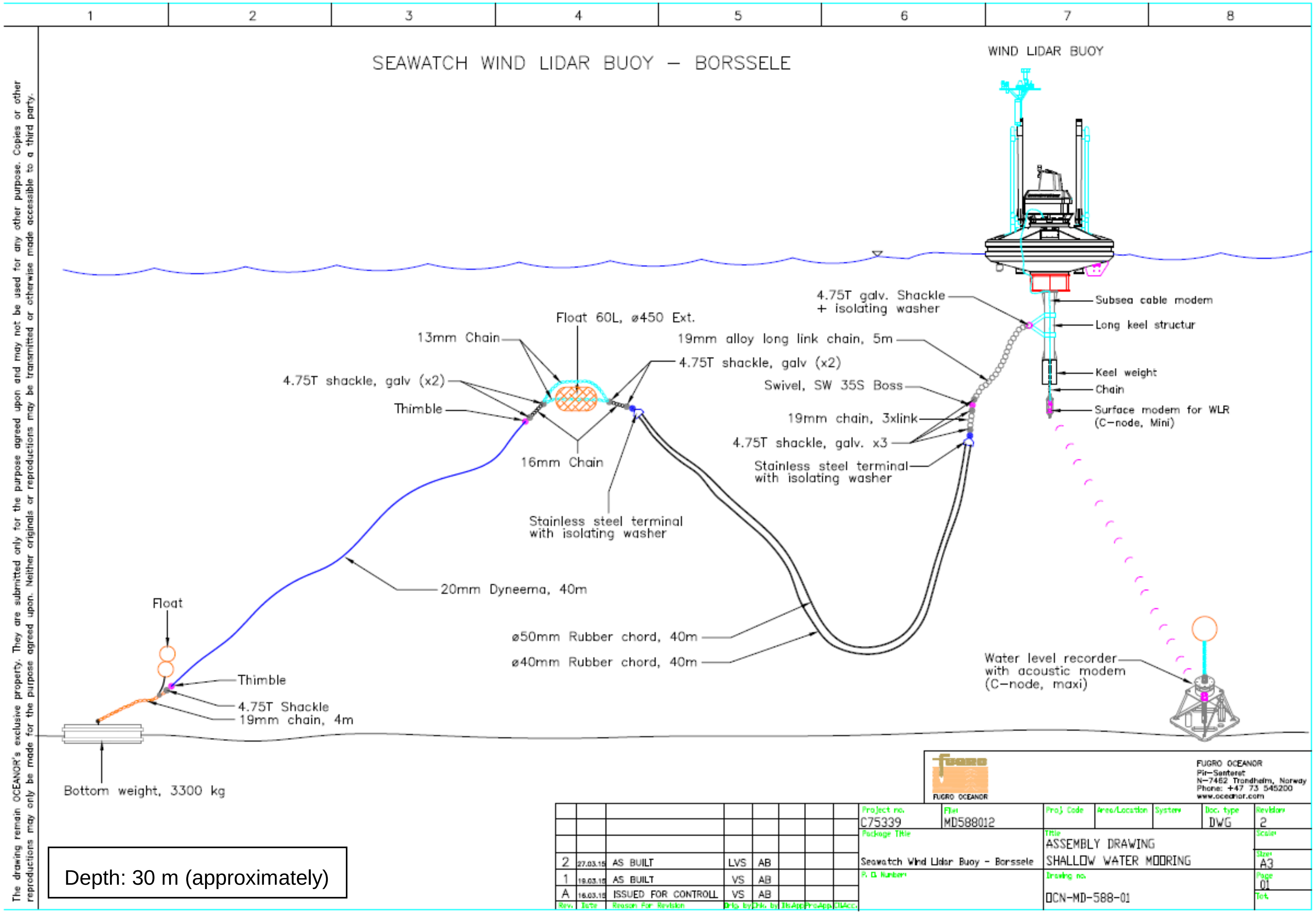

Figure 2.1 Mooring design for the Wind Lidar Buoy as deployed at Borssele Wind Farm Zone (BWFZ).

3. Results

3.1 Data recovery

The buoy transmitted data continuously from all sensors from 26 January at 23:00 until 27 February 2017 at 11:50, with the exception of some minor gaps. For the short gaps in the Lidar data the received data are replaced by the "missing data" flag at all heights. The longest data gaps occurred on 29th of January and 9th and 18th of February. Due to the gaps it took 31.535 days to collect 30.5 days of good wind profile data[1].

The air temperature and humidity sensor has previously been reported to have low availability due to repeated subsequent equal values. There is no gap in the data, but two or more subsequent equal values have been interpreted as a sensor error and the value has been replaced by NaN. The Vaisala HMP155 sensor is reporting two values; air temperature and relative humidity. The filtering we have applied earlier had the condition that if both air temperature and humidity reported repeated values, the repeated value was replaced by NaN. The data resolution for air temperature has been close to 0.1 ^{o}C and the data resolution for humidity has been 0.1 % in the buoy config. In other words we have applied an acceptance criteria saying that air temperature must change more than 0.1 ^{o}C or the humidity must change more than 0.1 % in 10 min in order for the data to be accepted as good. This was obviously too strict and we have unfortunately removed good values from the data set in previous periods causing a too low availability for air temperature and humidity.

We have now modified the acceptance criteria to the condition that if both air temperature and humidity reported repeated values for more than 3 subsequent measurements (30 min), the repeated value is replaced by NaN.

The number of hours of good data compared to the total obtainable hours of data is presented in Table 3.1.

Table 3.1 Data return during the period 26 January at 23:00– 27 February 2017 at 11:50.

Measurement device	Length of data period (days)	Length of data set (days)	Average availability (%)
Lidar wind profile sensor	31.535	30.500	96.718
Wave sensor	31.535	31.235	99.053
Current velocity sensor	31.535	31.299	99.251
Atmospheric pressure sensor	31.535	31.305	99.273
Air temperature sensor	31.535	30.687	97.314
Water Level Sensor *	31.535	0	0.00

* The real time transmitted water level data are unexpectedly lost due to breakdown of the acoustic link. However, the complete data series will be recovered if the instrument is recovered.

[1] Additional gaps in the real time transmitted Turbulence Intensity (TI) data are caused by breaks in the satellite dial-up transmission link. The data that were not received in real time are stored internally in the buoy and will be downloaded from the buoy when it is recovered.

3.2 Reference stations

3.2.1 Positions and distances

Two public reference stations are used in the validation of the data. The reference for the wave measurements is a Waverider buoy at Schouwenbank (SCHB). For wind the reference is the station at Vlakte van de Raan (VR). The positions of the stations are given in Table 3.2, which gives an overview of the locations and distances.

Table 3.2 Positions of the Lidar buoy and the reference stations used in the evaluation of the buoy data.

Station	Latitude	Longitude	Distance from the Lidar buoy	Shortest distance from land
Borssele Lidar buoy	51° 42.41’ N	3° 2.08’ E		32.5 km
Schouwenbank Waverider buoy (SCHB)	51° 44.8’ N	3° 18.3’ E	19.3 km	22.0 km
Vlakte van de Raan (VR)	51° 30.0’ N	3° 15.0’ E	27.6 km	12.2 km

3.2.2 Schouwenbank

The wave measuring buoy at Schouwenbank (SCHB station) is a directional (“2D”) Datawell Waverider buoy. This buoy measures the wave height and directional spectrum using 3-axis accelerometers.

The SCHB station should be expected to have lower heights of wind sea than the Borssele Lidar buoy location in southerly to north-easterly winds due to the more limited fetch distance in those directions. In situations with wind sea from north-east to north-west, and situations dominated by northerly swells the two buoy should be exposed to approximately the same wave heights.

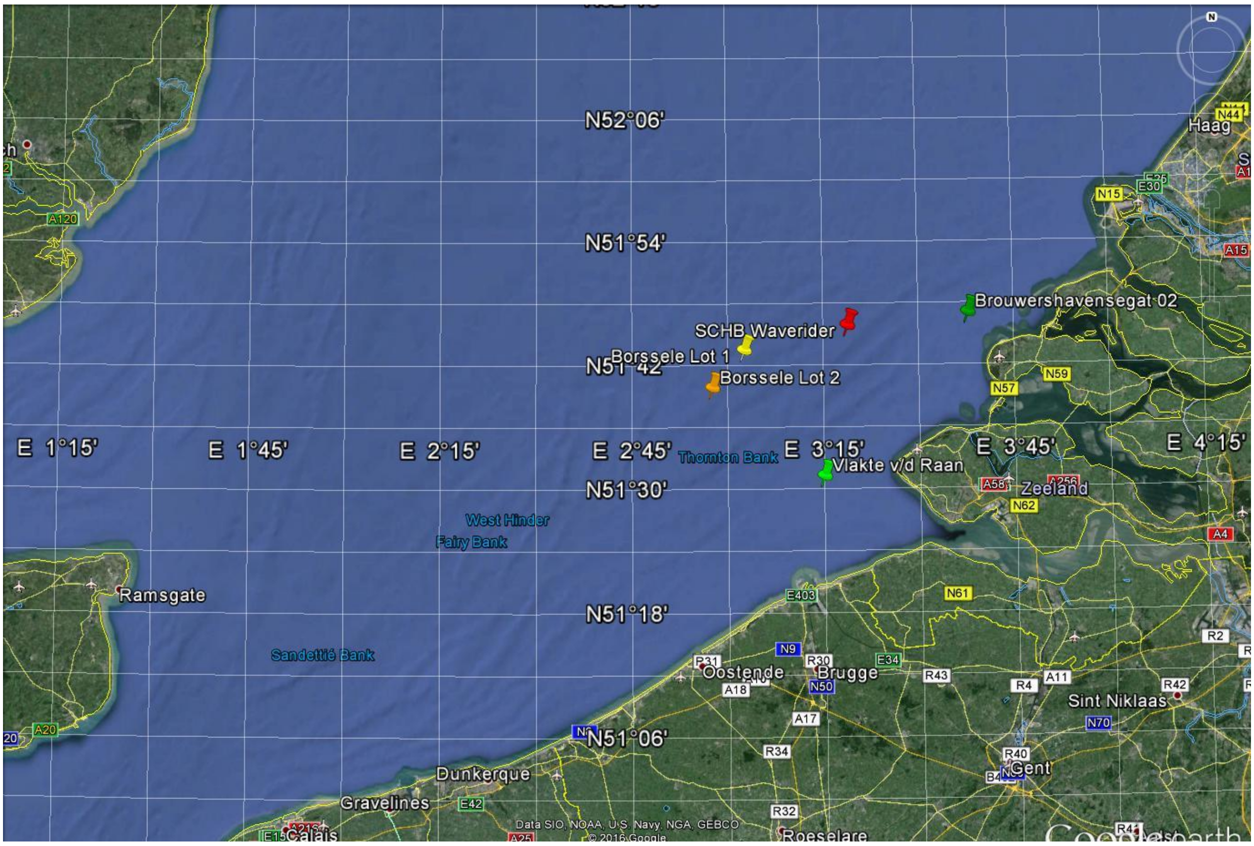

Figure 3.1 Google Earth image indicating Lidar buoy Lot 1 and 2 positions and reference stations. (The Borssele Lot 1 Lidar buoy which is validated in this report is marked by the bright yellow pin.)

3.2.3 Vlakte van de Raan

The Vlakte van de Raan (VR) station is measuring wind speed and wind direction. Figure 3.2 shows a photo of the wind mast. Wind speed is measured with the KNMI cup-anemometer. Cup diameter is 105 mm and the distance between the centre of the cups to the rotation axis is 100 mm. Wind direction is measured with the KNMI wind vane. Distance between axis and the outer side of the vane is 535 mm. The anemometer and wind vane are located 13.9 m above the mean sea level. The azimuth of the wind vane plugs at the tip of the booms are determined with a camera relative to distant objects at close to the horizon. The instruments are logged with the KNMI wind SIAM. Wind gusts are determined from a running 3 sec mean value.

Figure 3.2 The wind measuring station at Vlakte van de Raan.

Calibration of the cup anemometers is done in the wind tunnel of KNMI. Wind vanes are balanced and the direction of the vane is tested. Sensors are replaced after 26 month. The cup anemometer contains a photo-chopper with 32 slits. The accuracy is 0.5 m/s. The threshold velocity is 0.5 m/s. The resolution is 0.1 m/s. The response length is 2.5 m. The wind vane contains a code disk. Accuracy is 3°. Resolution is 1°. [ref. Chapter 5 "Handbook for the Meteorological Observation. Koninklijk Nederlands Meteorologisch Instituut KNMI, De Bilt September 2000.]

The VR station is located only 12 km from the coast and much closer to land than the Lidar buoy, and that is expected to have some effect on the winds, both speed and direction, especially for wind with direction from shore; directions from south-southwest to east-northeast in particular. This means that there can be considerable differences in wind speed and direction at any given time, while the long term overall averages are expected to be approximately the same.

3.3 Evaluation of the collected data

3.3.1 Wave data

The wave data from the Lidar buoy are compared to data from the Waverider at Schouwenbank in time series and scatter plots. The distance of about 20 km between the two locations and the different distance from shore is expected to cause some differences in these shallow waters.

The time series plot in Figure 3.3 and scatter plot in Figure 3.4 compare the significant wave height (Hm0). All peaks in the time series occur at almost exactly the same time, showing good coherence. The average Hm0 values are 1.10 m at the Lidar buoy compared to 1.01 m at Schouwenbank. The difference as well as the scatter with R^2 = 0.948 may be attributed to differences between the locations. The water depth is different at the two locations, with SCHB being the shallower, and this would explain why the wave height is systematically lower at SCHB compared to the Lidar buoy at higher sea states, while they are the same at low sea states. The different distance from shore would give lower waves at SCHB when there is wind from shore due to the more limited fetch.

The waves this month has been lower than previous months and this will lead to more scatter (lower R^2) when wave height are compare over some distance. Keeping this in mind we see that the Lidar buoy data compares remarkably well to the reference.

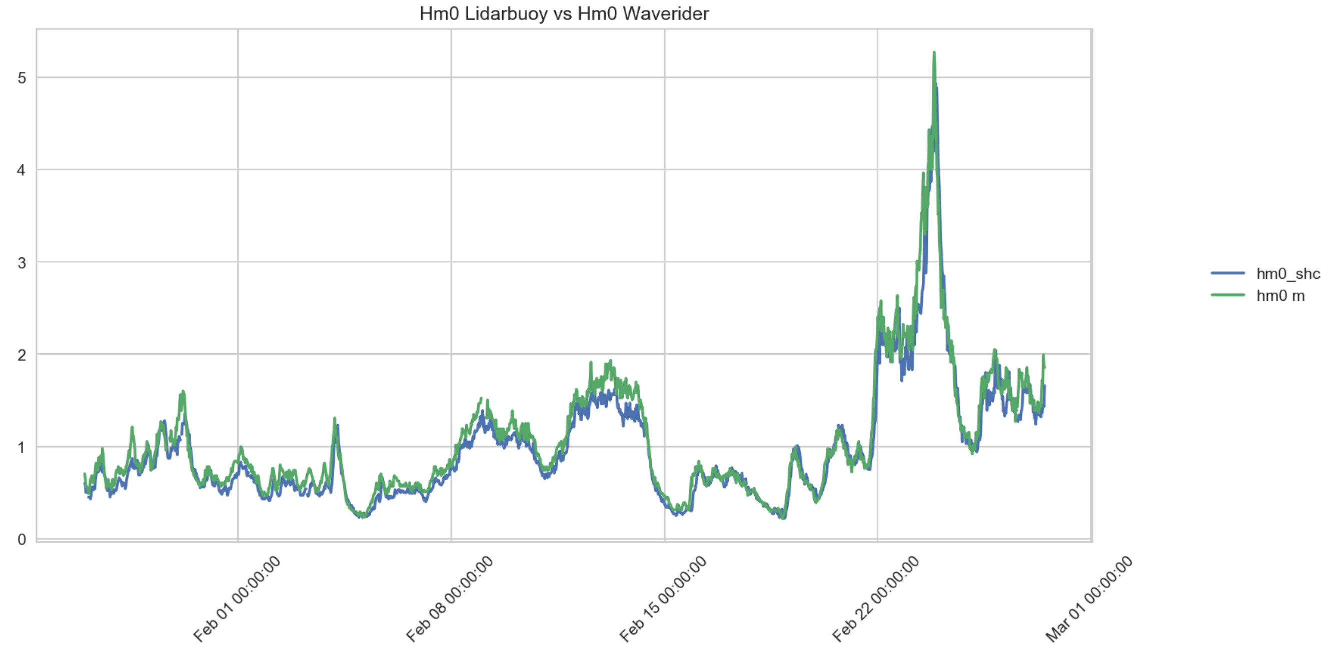

Figure 3.3 Time series plot of significant wave height (Hm0) from the Lidar buoy (green curve) and the Schouwenbank Waverider buoy (blue).

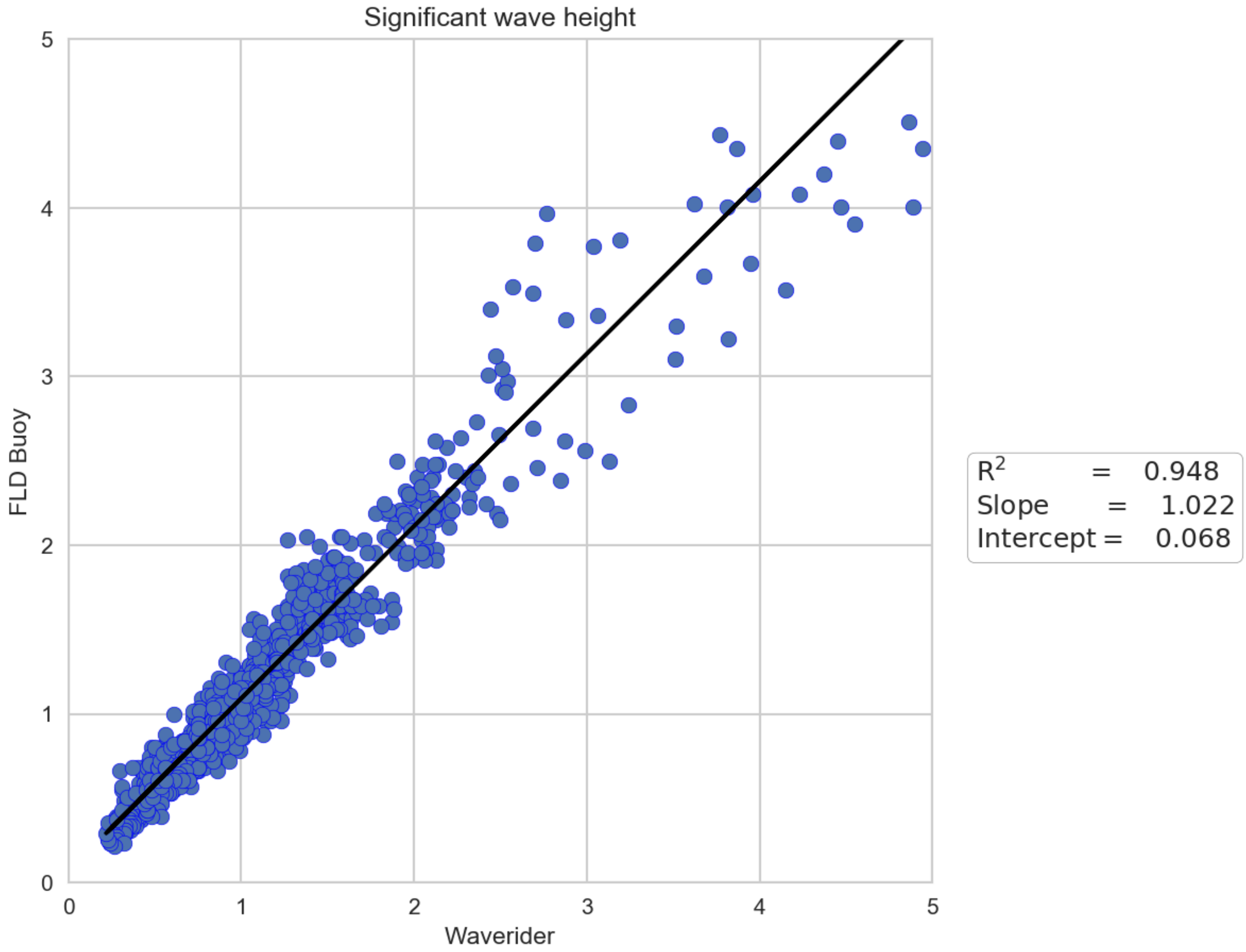

Figure 3.4 Scatter plot comparing Hm0 measured by the Lidar buoy to Hm0 from the Schouwenbank Waverider buoy.

The mean wave period (Tm02) from the Lidar buoy is compared to the Waverider Tm02 in the time series plot in Figure 3.5 and the scatter plot in Figure 3.6. The time series plot shows good coherence and the values appear very similar. The scatter plot shows R^2 = 0.860. Some scatter must be expected due to the distance between the stations. The average values of Tm02 are 4.14 s at the Lidar buoy compared to 4.02 s at the Waverider.

The waves this month has been lower and shorter than previous months and this will lead to more scatter (lower R^2) when wave height and period are compare over some distance.

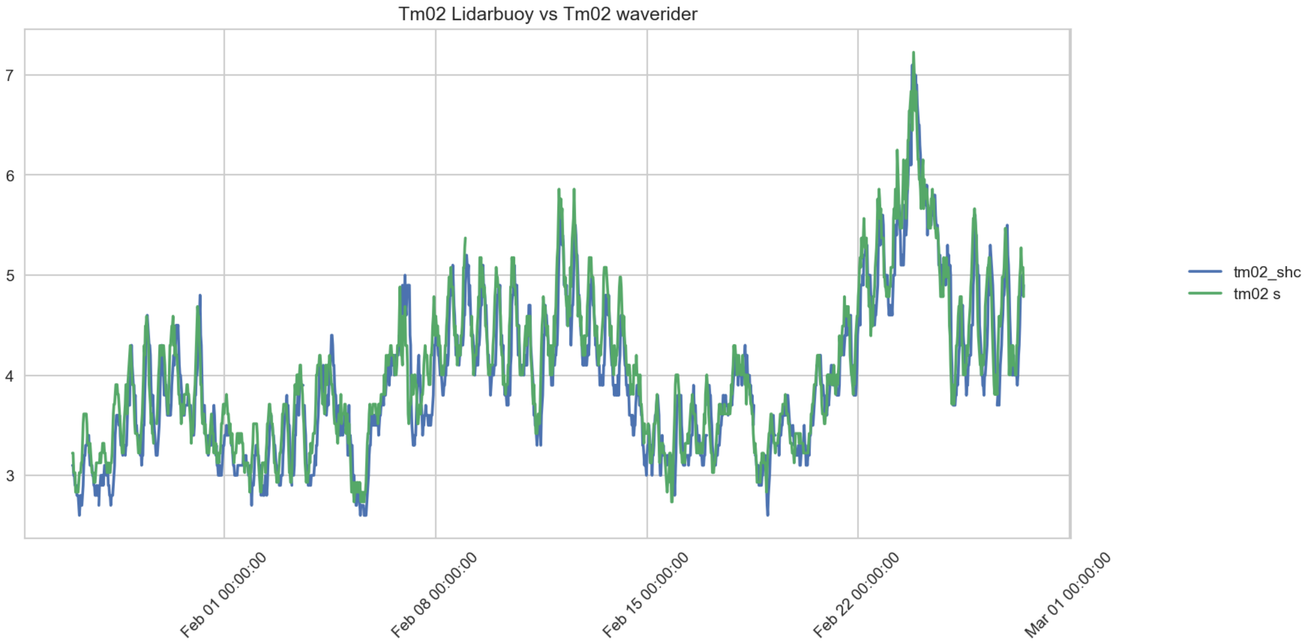

Figure 3.5 Time series plot of mean wave period (Tm02) from the Lidar buoy (green curve) and the Schouwenbank Waverider buoy (blue).

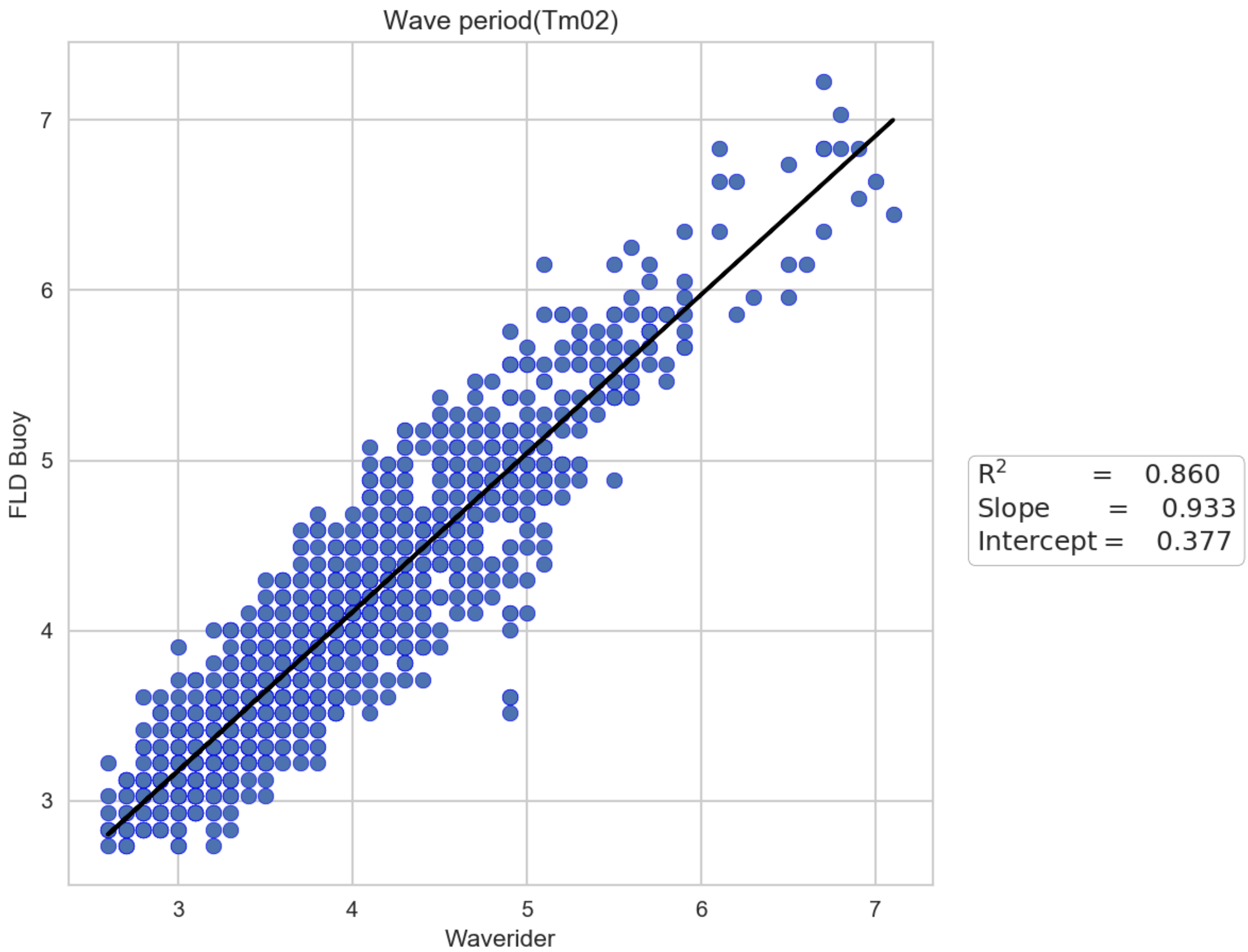

Figure 3.6 Scatter plot comparing Tm02 measured by the Lidar buoy toTm02 from the Schouwenbank Waverider buoy.

3.3.2 Wind data

The Vlakte van de Raan (VR) wind station is located about 28 km away from the Lidar buoy and much closer to shore. The VR station is about 12 km from the nearest shore, while the buoy is 33 km from land. The wind speeds measured at anemometer height, 13.9 m above the mean sea level, have been reduced to 10 m above mean sea level by a factor of 0.95. The horizontal Lidar wind speed data from the lowest cell, at 30 m above the sea surface, have been compared to the wind data from VR adjusted from 10 m to 30 m height by a factor of 1.15. The data series presented in Figure 3.7 show a similar behaviour as the maxima in wind speed at both locations appear at the same time, showing good coherence. On average the buoy show slightly higher average speed at 30 m height than the VR station, the values are 8.86 m/s at the buoy and 8.75 m/s at VR.

The scatter plot in Figure 3.8 compares the wind speeds when the VR station speeds exceed 2 m/s. The correlation is seen clearly; R^2= 0.972. The scatter and the slope of 1.013 in the regression line are probably due to the distance between the stations and the differences in the way land effects influence the local wind. Still the wind data compares remarkably well to the reference and better than in previous months. Most likely the reason is that the wind in this period has been more stable than in previous months. This confirms that there is no reason to suspect that the Lidar has not measured the wind speed correctly.

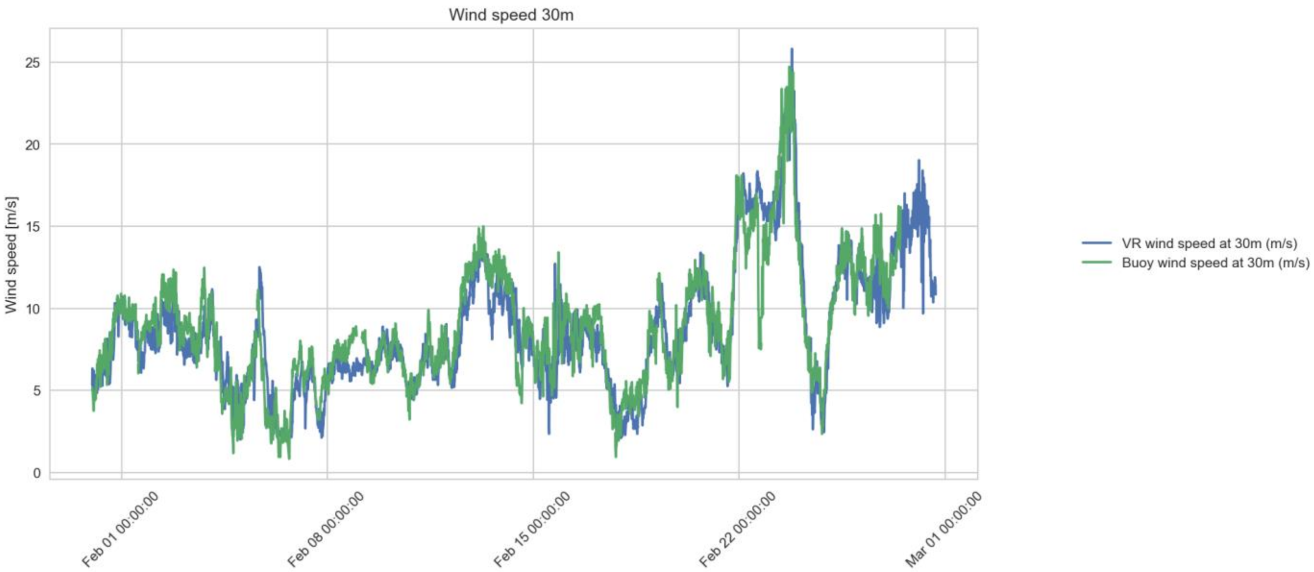

Figure 3.7 Wind speed at 30 m above sea level measured by the Lidar buoy (green curve) compared to wind speed at Vlakte van de Raan adjusted to 30 m (blue).

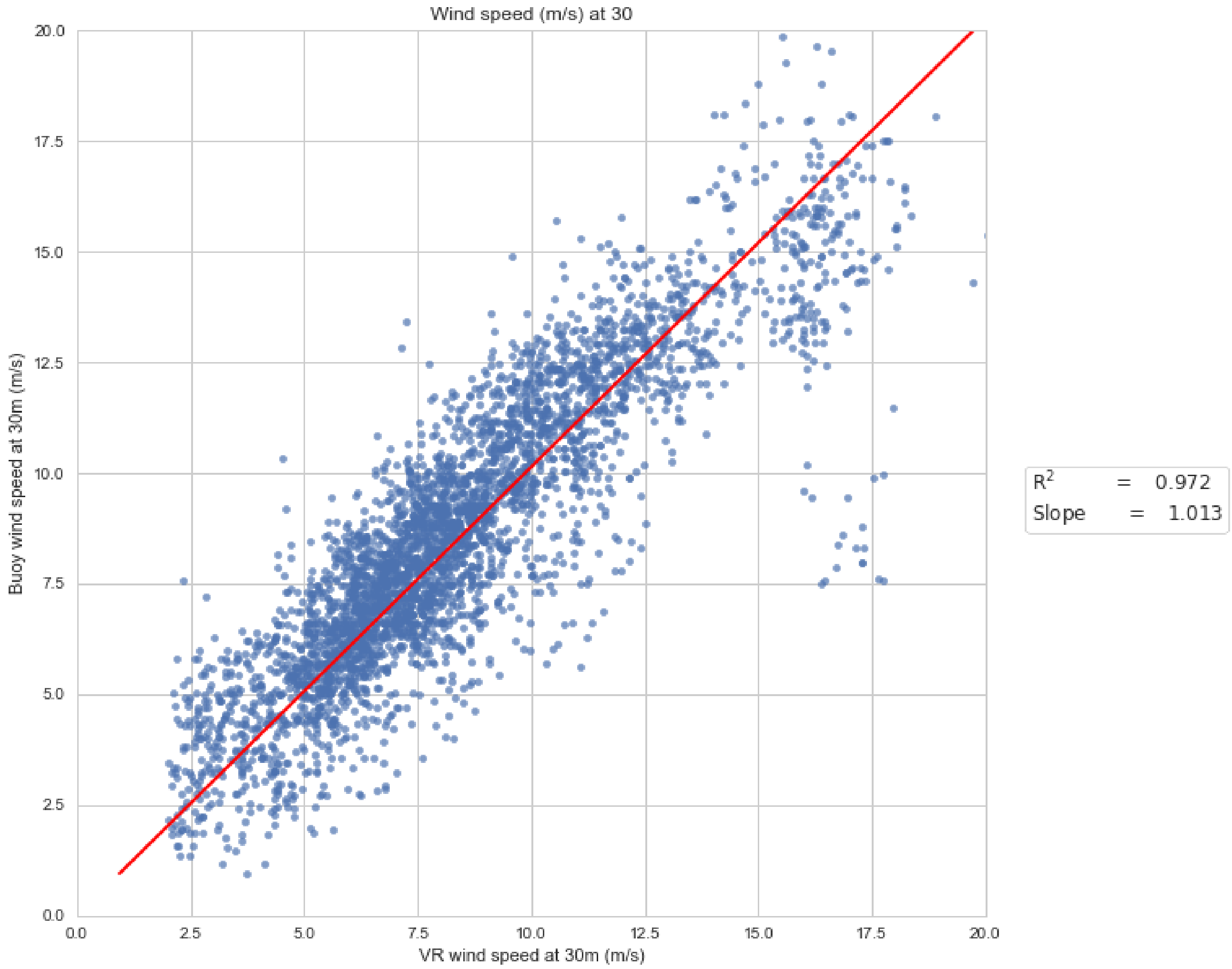

Figure 3.8 Scatter plot comparing the wind speed at 30 m above sea level measured by the Lidar buoy to the wind speed at Vlakte van de Raan adjusted to 30 m a.s.l. (Regression formula: y = Slope * x)

The time series of wind direction are compared in Figure 3.9, which also shows the wind speed at Vlakte van de Raan. Samples with speed less than 2 m/s are excluded. Again we see that there is a general agreement between the measurements, and this is seen also in the scatter plot in Figure 3.10. The offset between the wind directions is calculated as the average of the difference between the wind directions. It should be expected that the wind directions differ at any given time due to the distance between the locations, and this explains the limited scatter seen in the plot. The plot in Figure 3.10 shows that the wind directions in this period were spread on all directions. The correlation is good taking the distance between the stations into account, correlation factor R^2 = 0.967.

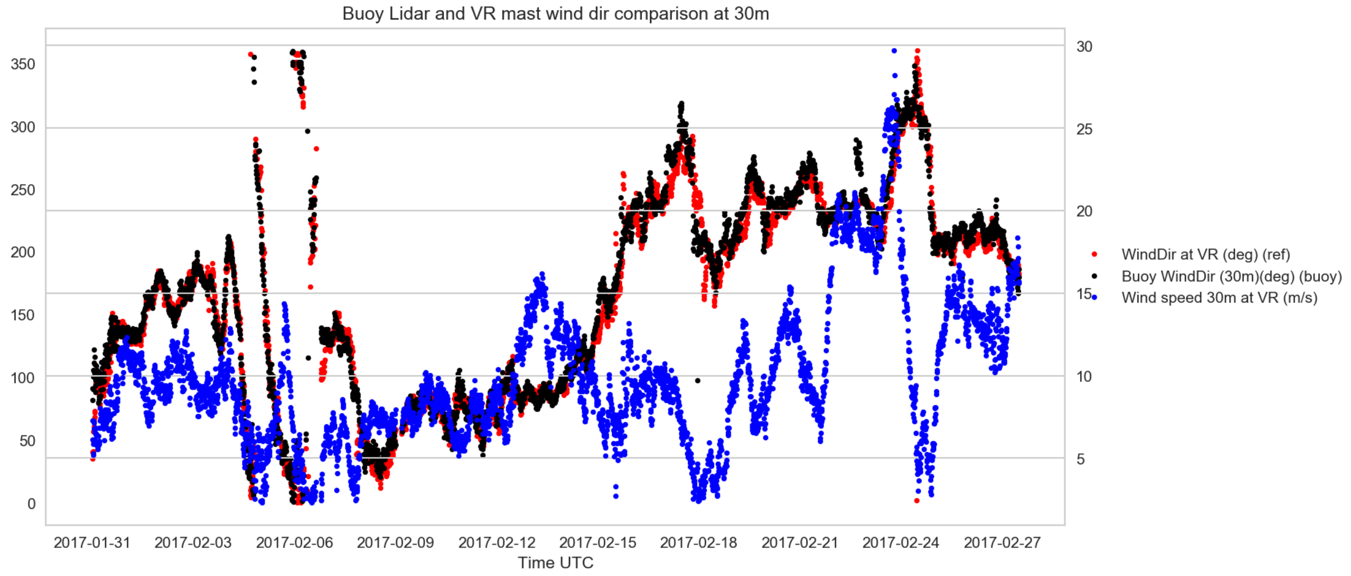

Figure 3.9 Wind direction at 30 m above sea level measured by the Lidar buoy (black dots) compared to wind direction at Vlakte van de Raan. (red). The blue dots show the VR station 10m wind speeds. (Samples with VR wind speed less than 2 m/s are excluded.)

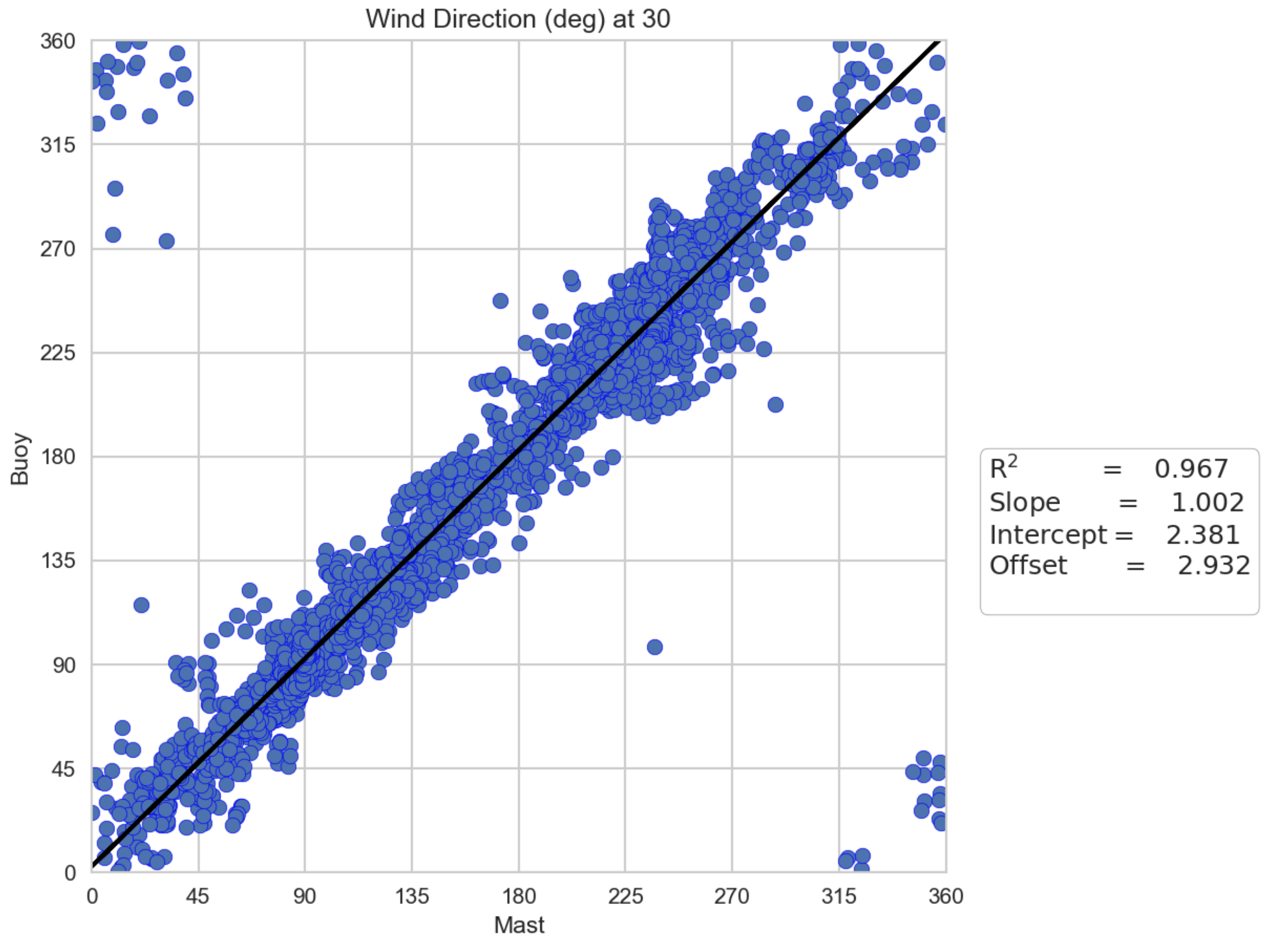

Figure 3.10 Wind direction at 30 m above sea level measured by the Lidar buoy compared to wind direction at Vlakte van de Raan. (Samples with VR wind speed less than 2 m/s are excluded.) ("Offset" is the average difference of directions.)

3.4 Conclusions

The comparisons to the reference station data presented above indicate that the buoy has collected data of good quality for winds and waves. The Seawatch Wind Lidar buoy has transmitted data almost continuously during the month. There are one major and a few short gaps in the Lidar data where the received data are replaced by the “missing data” flag at all heights. Due to the gaps it took 31.535 days to collect 30.5 days of good wind profile data.

Appendix A

Appendix A	DEPLOYMENT/RECOVERY SHEET			
Project Name: Borselle				
Project no: C75339	Latitude: 51°42.41388'N			
Station name: Borselle Lot 1	Longitude: 3°2.07708'E			
WS buoy no: WS157	Approx. depth: 30m			
PFF numbers:	Buoy marking: YES			
Buoy module/sensor	**Serial number/ID**			
CONFIGURATION				
Data transmission interval:				
Listening window				
POWER OPTIONS				
Lead batteries type				
DEPLOYMENT HISTORY				
	YEAR	**MONTH**	**DATE**	**GMT**
First measurement	2016	february	12	1200
First measurement this deployment	2016	december	12	1205
Out of measuring position				
Last measurement				
Comments: WS157 attatched to the Borselle Lot 1 mooring.				
WS157 deployment vessel: Multrasalvor 3	WS157 deployed by: Lars Slettemark			